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THE MEASUREMENT OF AIR QUANTITIES AND ENERGY LOSSES IN MINE ENTRIES

PART IV

BY

CLOYDE M. SMITH

ILLINOIS COAL MINING INVESTIGATIONS COÖPERATIVE AGREEMENT

(THIS REPORT WAS PREPARED UNDER A COÖPERATIVE AGREEMENT BETWEEN THE ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS AND THE ILLINOIS STATE GEOLOGICAL SURVEY)

BULLETIN No. 199

ENGINEERING EXPERIMENT STATION

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THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Industrial Chemistry. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps composed of full-time research assistants, research graduate assistants, and special investigators.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University of Illinois; *either above the title or below the seal is given the number of the Engineering Experiment Station bulletin or circular which should be used in referring to these publications.*

The present bulletin is issued under a coöperative agreement between the Engineering Experiment Station of the University of Illinois and the State Geological Survey. The reports of this coöperative investigation are issued in the form of bulletins by the Engineering Experiment Station, the State Geological Survey, and the United States Bureau of Mines, formerly a partner to the agreement. For bulletins issued by the Engineering Experiment Station, address Engineering Experiment Station, Urbana, Illinois; for those issued by the State Geological Survey, address State Geological Survey, Urbana, Illinois; and for those issued by the United States Bureau of Mines, address the Director, United States Bureau of Mines, Washington, D. C.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 199 DECEMBER, 1929

THE MEASUREMENT OF AIR QUANTITIES AND ENERGY LOSSES IN MINE ENTRIES

PART IV

INVESTIGATIONS IN TIMBERED ENTRIES

BY

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE MEASUREMENT OF AIR QUANTITIES AND ENERGY LOSSES IN MINE ENTRIES

Part IV

Investigations in Timbered Entries

I. Introduction

1. *Relation of Investigation to Previous Work.*—Following the conclusion of the third season's work as reported in Part III* of the present series, it was desired to extend the work along the lines previously developed to include some timbered entries, and, if possible, some resistance zones in which the character of the timbering could be changed at will. Two mines were visited in each of which the resistances offered to the flow of air by timbered entry was measured, and in one of which it was possible to modify the timbering under certain conditions as described in the body of the report.

2. *Acknowledgments.*—The field work was in charge of the author who was also responsible for the reduction of the field data and their interpretation. Mr. David R. Mitchell, Associate in Mining Engineering, and Dr. P. C. Hsu assisted in the field work.

The courtesy of the Matthiessen and Hegeler Zinc Company in permitting this work to be done at their coal mine at LaSalle, Illinois, and of the Sunlight Coal Company in encouraging and facilitating the work at their mine at Verona, Illinois, is gratefully acknowledged. Special mention should be made of the interest and splendid coöperation of Mr. E. J. Weimer, superintendent of the Verona Mine.

The investigation was carried on under a coöperative agreement between the Engineering Experiment Station of the University of Illinois and the Illinois State Geological Survey, and has been a part of the regular work of the Engineering Experiment Station of which Dean Milo S. Ketchum is the director, and of the Department of Mining Engineering of which Prof. Alfred C. Callen is the head.

II. Work at the Matthiessen and Hegeler Mine

3. *Description of Aircourse.*—This mine is ventilated by a Sirocco Number 12, six-by-two-foot centrifugal blowing fan, electrically driven at about 390 r.p.m. The water gage of the mine is nearly six inches. The shaft is 310 feet deep and the air compartment

*Bulletin 184.

is 8 by 8 feet in cross-section. There is no sump at the shaft bottom. All the air, save of course the leakage, makes an abrupt vertical right-angled bend into the single main aircourse.

From the shaft the aircourse is nearly straight for about 50 feet, then it deflects about 15 or 20 degrees to the left, whence it is again virtually straight for another 150 feet, to a junction with a cross-entry to the left which the air current follows, the main entry being closed with doors farther inbye. These features are shown in Fig. 1, which also shows all of the timber sets, the cross-section diagrams, the roof and floor profiles and area and perimeter curves, both inside and outside of the timbers. The cross-sections were located, in general, by taking one between two adjacent timber sets, then one in the downstream set of the two. The next inter-timber space was skipped, then the process repeated, giving, where carried out ideally, a cross-section for every alternate space and timber set.

The entry was supported with three-piece sets of 6- to 8-inch timber. Most of the cross-bars were square in cross-section, while the props were usually round. The spacing of the sets, while very irregular, averaged about 3 feet on centers. The ribs were thoroughly lagged with either round or square posts, save for some short, irregularly spaced, lengths of pack wall which stood close against the props in most cases, and were reasonably smooth. Very few timbers were broken, and there were only one or two abrupt irregularities in the inside cross-section of the entry, which still had some track in it.

No evidence of the location of former cross-cuts was found nor could any leakage out of the entry be detected, although it is possible that some took place through the lagging and gobbed walls into old workings. This possibility was ignored in the computations, it being assumed that the same quantity flowed through all cross-sections in question.

4. *Subdivision of Entry.*—The upstream static section, A_1, (Fig. 1) was put at the bend in the entry about 50 feet from the shaft to include the maximum length of straight entry below this point. The traverse section A_2 was put in a timber set as near the downstream bend as practicable, and a lower static section A_3 to include the straightaway at $1 + 90$ just above the bend. The bend itself was included between sections A_3 and B_1 (Fig. 1), the instrument station being located farther inbye along the straight entry.

5. *Quantity Measurements.*—Quantities were determined by the method of subsectional pitot-tube traversing previously employed.*

*See Bulletins 158, 170, and 184.

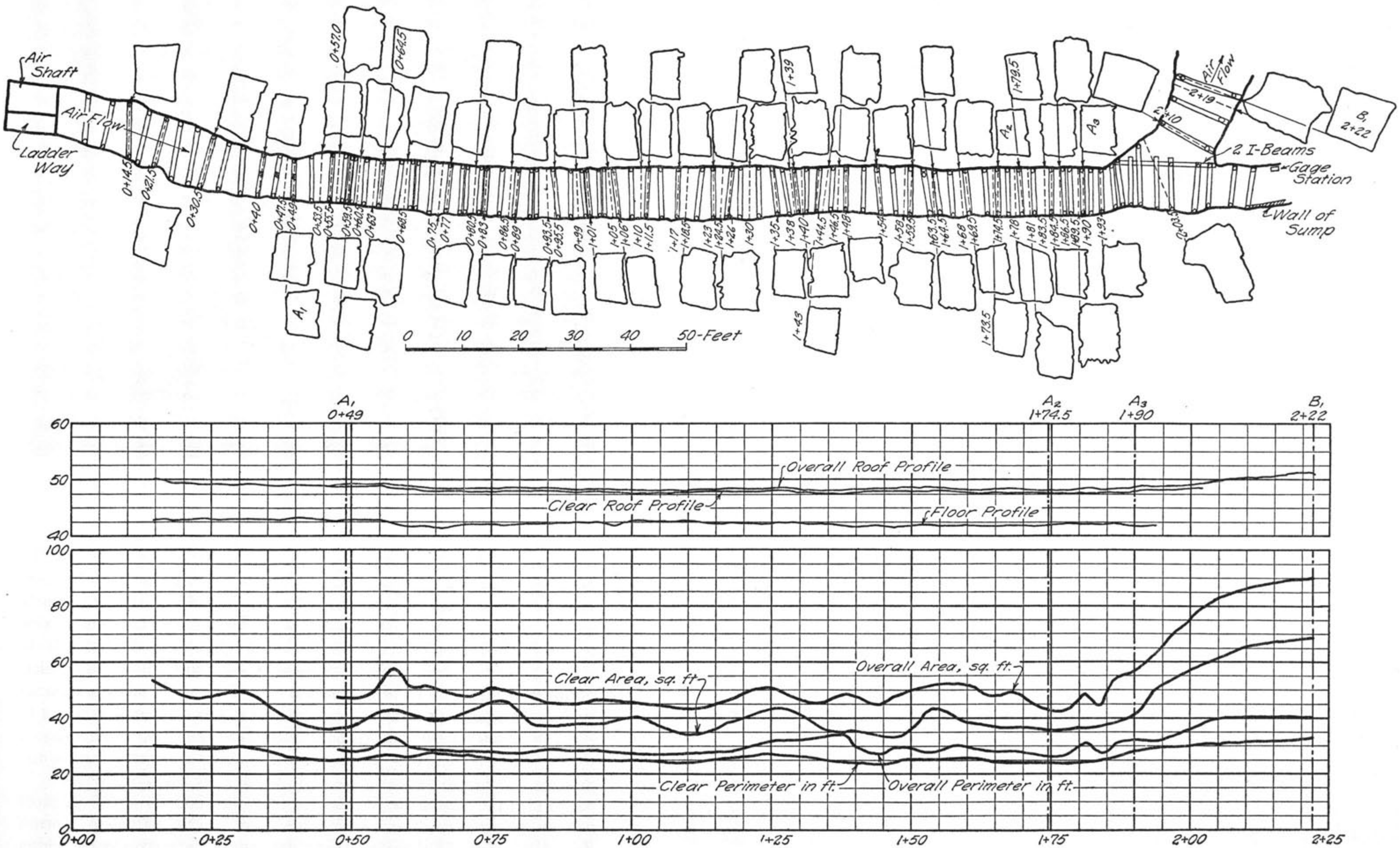

Fig. 1. Portion of Main Aircourse, Matthiessen and Hegeler Mine

FIG. 2. LOOKING DOWNSTREAM THROUGH SECTION A_2, MATTHIESSEN AND HEGELER MINE

All the traversing in this mine was done at section A_2, the outlines and method of subdivision of which are shown in Fig. 2. The scheme of alternating the number of points in successive tiers from four to three was an unusual one, adopted as a means of approaching the periphery of the section as closely as possible with a moderate number of points (18), still retaining a reasonably uniform distribution of points throughout the section. It was planned later to increase the number of traverse points on the usual gridiron pattern to perhaps 25, to give a comparison between results obtained by the two methods, but circumstances prevented this extension of the work.

Eleven traverses were made at this section, at quantities ranging from 20 000 to 68 000 cubic feet per minute, six determinations of the normal quantity giving very consistent results averaging 45 400 cubic feet per minute. Some men were working in the mine, although no coal was being hoisted, while the normal-quantity traversing was in progress. Quantities less than normal were obtained by running a small auxiliary high-speed centrifugal fan driven by a steam turbine

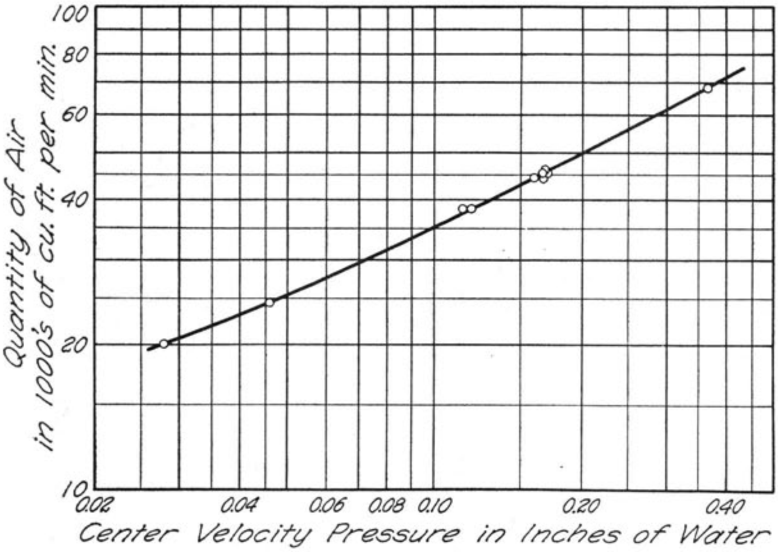

FIG. 3. RELATION OF QUANTITY TO CENTER VELOCITY PRESSURE, SECTION A_2

in place of the regular fan, and the one quantity higher than normal by opening the doors in the straight entry just inbye the instrument station, thereby shortening the airflow into the return aircourses. The relationship between quantity and net center velocity pressure is shown in Fig. 3 where quantity, plotted logarithmically against net center velocity pressure, is represented by a curve of slight upward concavity, its slope being nearly one-half, as is to be expected from the fact that the velocity at a point is proportional to the square root (or one-half power) of the velocity pressure.

6. *Isovels.*—An isovel diagram was drawn for each traverse of the season's work. Those for section A_2 were all of the centered bull's-eye type, being much alike in appearance irrespective of the quantity. A diagram representing normal conditions is shown in Fig. 4. In all of the isovel diagrams for this section there is a low velocity area about the lower half of the vertical center line which is much more marked in some of the diagrams than in Fig. 4. It is possibly due to the presence of the center pitot tube supporting stand just a few inches downstream from the traverse section. A similar condition was noted in previous work,* although the evidence at that time tended to show that the effect was not produced by the stand.

*See Bulletin 170, page 61.

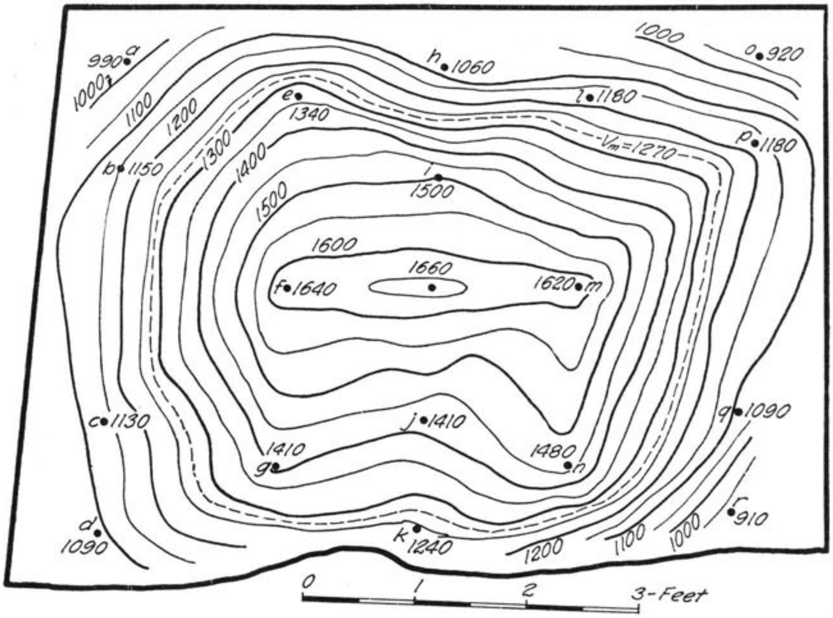

FIG. 4. ISOVEL DIAGRAM, NORMAL QUANTITY, SECTION A_2

7. *Pressure and Energy Losses.*—Differential static pressure readings were taken between cross-sections A_1, A_2, A_3, and B_1 established for this purpose during each of the 11 traverses at section A_2, and pressure and energy losses for the appropriate portions of the entry and quantity of airflow computed therefrom. Contrary to the previous season's experience* there was relatively little disagreement between the sum of the static pressure drops in consecutive resistance lengths and the observed static pressure drop for the corresponding overall length throughout this season's work, so only slight adjustments were necessary to make the data meet this obviously necessary condition.

The principal resistance unit studied was A_1 –A_2 which is straight and 125.5 feet in length. Nine pressure loss determinations were made at quantities of from 20 000 to 68 000 cubic feet per minute; one quantity determination was based on center velocity pressure readings only, the quantity being read from Fig. 3. Of equal importance, and almost identical with A_1–A_2, is A_1–A_3 which, of course, includes A_1–A_2 (see Fig. 1) but is 141.0 feet long. Seven pressure loss determinations were made for this unit, two being dependent on center velocity pressure readings only for the quantity.

*See Bulletin 184, page 24.

The presentation of the results of the static pressure drop measurements is a matter of no little difficulty. In the past* the energy loss has been plotted logarithmically against the quantity and could generally be represented by a straight line for a given resistance zone. This is equally true for the present data, but the objection to that manner of presentation is that the results for one zone are not readily comparable with those of another zone, at like quantities, unless the slopes of the two lines happen to be the same, which is unlikely. The advantages of logarithmic plotting are that it not only gives the results clearly and compactly but also permits the formulation of a simple empirical algebraic relationship between the energy losses and quantity or velocity as desired.

Since the customary ventilation factor k involves both the static pressure drop and the quantity, it might be thought sufficient to calculate k and ignore the energy losses, but grave difficulties enter here for timbered entries as will appear in the discussion to follow. It will be recalled that the standard ventilation formula is

$$R = 5.2ia = kloV^2 \tag{1}$$

whence

$$k = \frac{5.2ia}{loV^2} \tag{2}$$

which, substituting $\frac{q}{a}$ for V, becomes

$$k = \frac{5.2ia^3}{loq^2} \tag{3}$$

where

R = resistance to flow, in pounds per square foot.
i = total pressure loss in inches of water.
a = mean cross-sectional area of resistance zone in square feet.
l = length in feet.
o = mean perimeter in feet.
q = quantity of air flowing in cubic feet per minute.

While the standard formula, $R = kloV^2$ may have some virtue as an approximate relation between resistance to flow and the velocity of the air in ducts which are comparatively uniform in cross-section, it becomes quite meaningless in timbered entries or other entries in which the cross-section changes frequently and abruptly, for it is

*See Bulletins 170 and 184.

manifestly impossible to evaluate a and o for the calculation of k from formula (3) above. Indeed these two parameters (a = mean cross-sectional area, o = mean perimeter) cease to have physical meaning where the cross-sectional area of the entry is reduced precipitately by about 15 to 25 per cent at the upstream edge of a timber set and suddenly increased by a like amount at the downstream edge of the set. Obviously, it is impossible to say what the effective cross-section at a given point is, in so far as airflow is concerned, under such inordinately varied conditions. However, in lieu of any more rational means of expressing and interpreting the data, the development of which would seem to await further theoretical treatment and laboratory research, and in view of the extent to which k has become embedded in the literature of mine ventilation and in the minds of numerous investigators it is used as an arbitrary means of expressing the results of the present investigation.

To obviate the necessity of attempting to derive true mean cross-sectional areas a and perimeters o for substitution in formula (3) k is computed on two different bases, using the average dimensions outside the timbers for the "overall" k and those inside the timber sets for the "clear" k_c. The true value, if such can be conceived, presumably lies somewhere between these two extremes.

It is evident from formula (3) that for a given quantity a larger k is to be expected when computed on the overall dimensions than on the clear dimensions, because k is directly proportional to a^3 and inversely proportional to o so that an increase in cross-section, which in itself involves a relatively greater increase in a than in o, leads to a decided increase in k. These relationships are brought out in Table 1.

From the standpoint of the physical conditions connoted by values of k it would appear more logical to compute it on the basis of overall dimensions. It is possible, for example, for a stretch of untimbered entry with rather rough ribs to have a k of about 75×10^{-10}. If we now timber this entry with 3-piece timber sets it might easily have a k of 150×10^{-10}, based on overall dimensions. This is logical, for evidently the physical roughness has been greatly increased by timbering. However, if k were computed on the basis of the clear cross-section, it would have a value of perhaps 60×10^{-10}, which fails to convey a correct physical conception of the roughness of the timbered entry when comparing it with $k = 75 \times 10^{-10}$ for the untimbered entry.

In the longer straight units (A_1–A_2 and A_1–A_3) k averages roughly 150×10^{-10} on the basis of overall dimensions and about 90×10^{-10} based on the clear dimensions. The latter value is 10 per cent less

TABLE 1
VALUES OF k
Matthiessen and Hegeler Mine

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		Mean Overall		Mean Clear				
Zone	Length ft.	Area sq. ft.	Perimeter ft.	Area sq. ft.	Perimeter ft.	k*	k_c*	No. Determinations
A_1–A_2	125.5	48.2	29.1	38.9	25.7	151 ± 2.1	90 ± 1.2	9
A_1–A_3	141.0	48.2	29.1	38.8	25.7	157 ± 1.6	92 ± 1.3	7
A_2–A_3	15.5	47.5	29.0	37.4	25.8	192	105	1

*In units of 1×10^{-10}

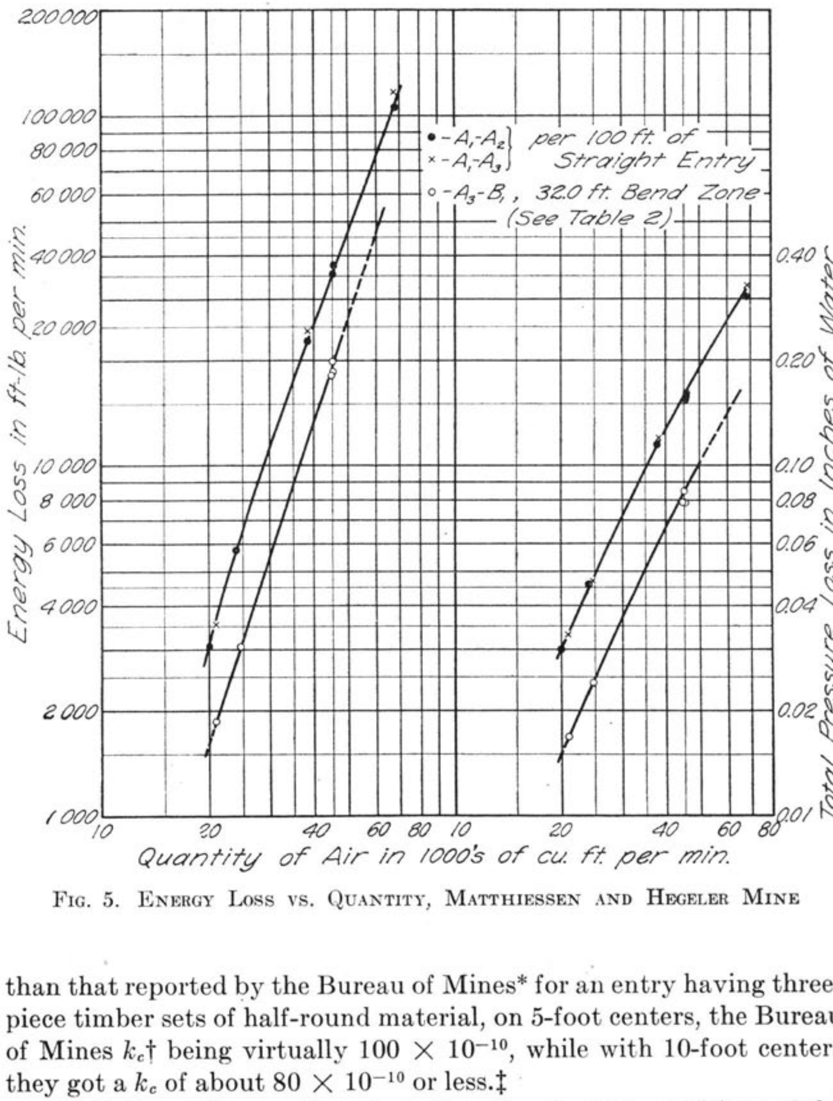

FIG. 5. ENERGY LOSS VS. QUANTITY, MATTHIESSEN AND HEGELER MINE

than that reported by the Bureau of Mines* for an entry having three-piece timber sets of half-round material, on 5-foot centers, the Bureau of Mines k_c† being virtually 100×10^{-10}, while with 10-foot centers they got a k_c of about 80×10^{-10} or less.‡

While it may be questioned whether the physical conditions of the test entries at these two mines were sufficiently similar to permit a comparison of the effect of spacing on k_c, it may be remarked in passing that laboratory investigation by Dr. P. C. Hsu§ has shown that there is a certain spacing for a given size of timber set that will

*Greenwald and McElroy, "Coal Mine Ventilation Factors," United States Bureau of Mines Bulletin 285, p. 45, 1929.

†In this bulletin k_c will always be used to represent the value computed for the "clear" dimensions.

‡Op. cit., p. 47.

§Unpublished thesis for the doctorate, University of Illinois. 1928.

TABLE 2

NET LOSSES DUE TO 70 DEG. BEND AND DEAD END, MATTHIESSEN AND HEGELER MINE

	Quantity (cu. ft. per min.)		
	20 000	40 000	60 000
1. Energy loss (ft. lb. per min. per 100 ft.) straight entry (A_1–A_2 and A_1–A_3)*	3 100	25 400	77 000
2. Energy loss (ft. lb. per min.) bend zone, (A_3–B_1)*	1 570	13 400	46 000
3. Energy loss (ft. lb. per min. per 32.0† ft.) straight entry $\left(= \frac{32}{100} \times \text{line } 1\right)$	990	8 130	24 650
4. Net energy loss due to bend (ft. lb. per min.) (2) − (3)	580	5 270	21 350
5. Equivalent length of bend (ft.) $\frac{(4)}{(1)} \times 100$	18.7	20.8	27.7
6. Total pressure loss (in. water per 100 feet) straight entry (A_1–A_2 and A_1–A_3)*	0.030	0.128	0.262
7. Total pressure loss (in. of water per 32.0 ft.) straight entry $\left(= \frac{32}{100} \times \text{line } 6\right)$	0.0096	0.0410	0.0840
8. Total pressure loss in. of water bend zone*	0.0155	0.067	0.143‡
9. Net total pressure loss due to bend (in. of water) (8) − (7)	0.0059	0.026	0.059
10. Mean cross-sectional area bend zone (sq. ft.) overall	80.6	80.6	80.6
clear	60.6	60.6	60.6
11. Mean velocity (V_m, in ft. per min.) overall	248	496	744
clear	330	661	991
12. Velocity pressure of V_m (in. of water) overall	0.0038	0.015	0.035
clear	0.0068	0.027	0.061
13. Ratio net total pressure loss due to bend to velocity pressure $\frac{(9)}{(12)}$ overall	1.6	1.7	1.7
clear	0.87	0.96	0.97

*From Fig. 5.
†Length along center line of A_3–B_1.
‡By uncertain extrapolation.

produce a maximum value of k or k_c, and that closer spacing will lower the friction factor.

To permit a deduction of the net energy loss due to the presence of the 70 deg. bend, dead end, and other irregularities between sections A_3 and B_1, the energy losses in the straight (A_1–A_3 and A_1–A_2) and bend (A_3–B_1) zones were plotted logarithmically against quantity in Fig. 5. By the interpolation of values from the two representative energy loss lines the calculation of the net energy loss due to the bend and other relations, at three assumed quantities, was carried out as shown in Table 2, which shows that the net bend-dead-end losses are equivalent to those of only about 15 feet of straight entry. This equivalent length apparently decreases with increasing quantity. The table also shows that the net loss is about 1.6 times the mean velocity pressure as calculated from the overall dimensions, and about 0.9 times the mean velocity pressure as calculated from the clear

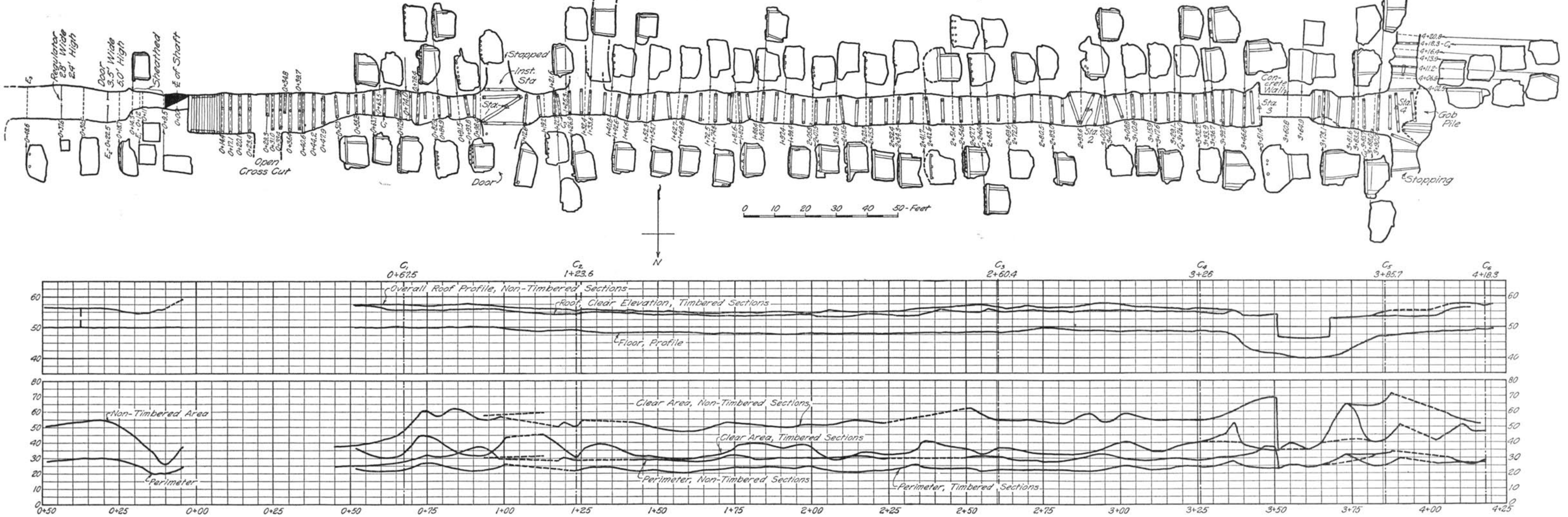

Fig. 6. Portion of Main Aircourses, Verona Mine

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dimensions. At like mean velocities (300 to 900 feet per minute) in an untimbered entry, the United States Bureau of Mines* found losses due to a right-angle bend with dead end to be 1.4 times the velocity pressure, a fair agreement with present findings, where the mean velocity pressure is derived from the overall dimensions. However, since the physical conditions of the two bend units are quite unlike, one being a right-angle bend in an untimbered entry, the other being a 70 deg. bend in a timbered entry, both having dead ends, it is probable that the approximate agreement in this item is largely accidental.

III. Verona Mine before Alteration

8. *Description.*—The Verona mine is a small, room-and-pillar shipping mine, located a short distance northeast of Verona, Grundy County, and operated by the Sunlight Coal Company. The airshaft is about 100 feet deep. The mine is ventilated by an electrically-driven centrifugal blowing fan operating at 200 r.p.m. At the bottom of the downcast shaft the air is split into two currents, the major portion of the total quantity going into the west aircourse, where most of the season's work was done, the remainder going into the east aircourse, which was regulated. These features are shown in Fig. 6, which gives the plan, roof and floor profiles, and cross-sectional characteristics of the aircourses adjacent to the shaft. The marked irregularity in plan, height, and in cross-sectional shape and area are evident from a glance at this figure.

West of the shaft, the aircourse is heavily timbered for a few feet with three-piece sets. These are followed by a series of four-piece sets, a center prop being added to the usual three-piece set where the entry is unusually wide. They continue for about 30 feet, then give way to a long series of irregularly-spaced three-piece sets, made up for the most part of 6- to 10-in. round timbers. The location of each set is shown in Fig. 6. The extent of the irregularities of outline of the entry are indicated by the plan and profiles of this figure, and the resultant cross-sectional areas and perimeters are shown in the lower curves. The same general scheme for locating cross-sections was followed here as at the Matthiessen and Hegeler mine.

The map is almost self-explanatory. Two roof profiles are carried, one for the non-timbered sections, and one for the elevations of the bottom of the cross-bar near the middle of the entry in the timbered cross-section. The former may be regarded as the overall roof profile,

*Op. cit., p. 68.

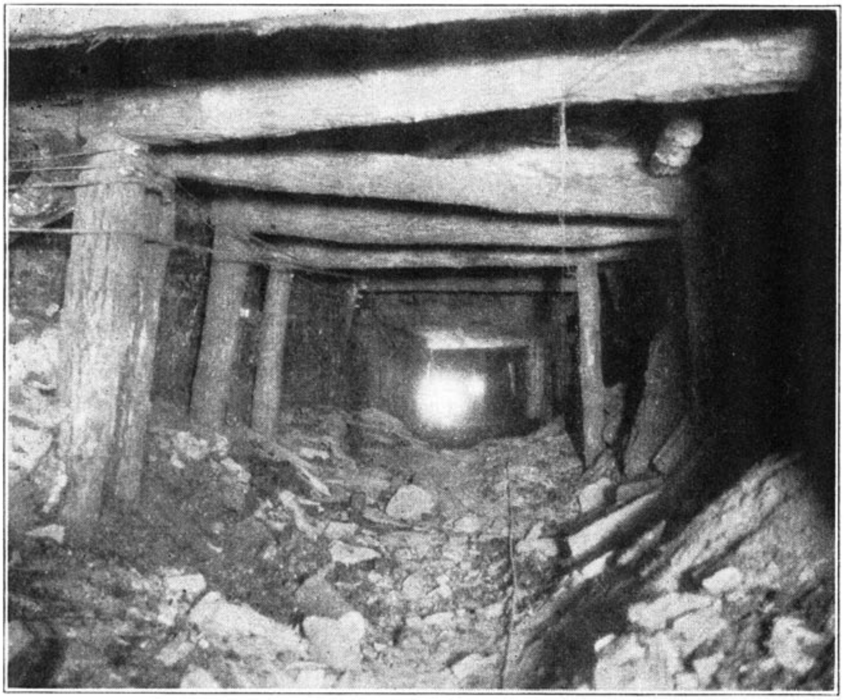

FIG. 7. LOOKING UPSTREAM THROUGH SECTION C_4, VERONA MINE

and the latter as the clear roof profile. The areas of the cross-sections represented by the upper roof profile (non-timbered sections) are shown on the uppermost area curve in the lower part of the figure. With this curve is more or less closely associated a group of points representing the overall area of the timbered sections, for, as will be seen from the cross-sectional diagrams, each of these cross-sections was completely mapped, showing not only the clear area, but also the timber set and entry outlines as well. The area curve corresponding to the lower roof profile (clear area of timbered sections) lies well below the upper curve, indicating a relatively large difference in the overall and clear cross-sectional areas. The upper and lower perimeter curves have relations to the upper and lower roof profiles with respect to cross-sectional perimeter, analogous to those of the upper and lower area curves to the roof profiles.

As to the grosser features of this aircourse, there is an open cross-cut to the right (looking downstream) at 0 + 30 (stationing from the center line of the shaft) which communicates with the east split outbye the regulator. At about 1 + 05 is an old cross-entry which communicates to the right through double doors (having, of course, some leakage) with the main bottom. To the left it is sealed with a concrete stopping about 40 feet from the aircourse. The instrument station was located in this chamber just off the aircourse (Fig. 6). The companion cross-entry is found at $1 + 33$, but it is completely gobbed up on the right, the left side being sealed like the left portion of the outbye cross-entry, just described. No leakage was detected through these seals. All former cross-cuts along this entry had been completely gobbed to the rib line of the aircourse, so that their existence was scarcely noticeable. At one of these, near the undercast, there was known to be a little leakage into the motor barn, and there were probably similar slight leakages elsewhere which were not detected. At $3 + 51$ a concrete undercast is encountered, which has abrupt approach and departure. The effect on the entry configuration is very marked, as is evident from Fig. 6. Leakage at the undercast seemed to be negligible. Immediately following this troubled zone a 90-deg. bend is turned to the left. There is a little leakage at the stopping to the right. After the bend, the entry continues on to the south, but no work was done in that region.

Going east from the airshaft, there is a marked drop in the roof height for about 5 feet resulting in sharp decreases in cross-sectional area and perimeter which is soon followed by a widening of the entry which greatly increases both area and perimeter, as shown by the respective curves (Fig. 6). Only two timber sets are present in this portion of the entry, with what amounts to two regulators, the upstream one having a small 5 x 3.5-ft. sliding man door, the downstream one, which really controls the airflow, having an opening 2.4 ft. high by 2.8 ft. wide.

9. *Subdivision.*—The first pressure-reading cross-section established was in the west aircourse at $0 + 67.5$. The upstream static section C_1 was placed here, in a timber set, as it was thought this was as far upstream as could safely be gone without encountering the effect of the constriction beginning at about $0 + 40$. Section C_2, the traverse section, was placed in a former regulator frame at $1 + 23.6$ to get the possible benefit of the reduced cross-sectional area, and the greater regularity of outline, and to be reasonably near the instrument station. Section C_3, an intermediate static section, is in a timber set at $2 + 60.4$, and C_4, the upstream section of the undercast unit C_4–C_5 is similarly situated at $3 + 26.0$, C_5 being on the other side of the undercast at $3 + 85.7$. All the static sections were arbitrarily placed in timber sets for the sake of uniformity. Whether or

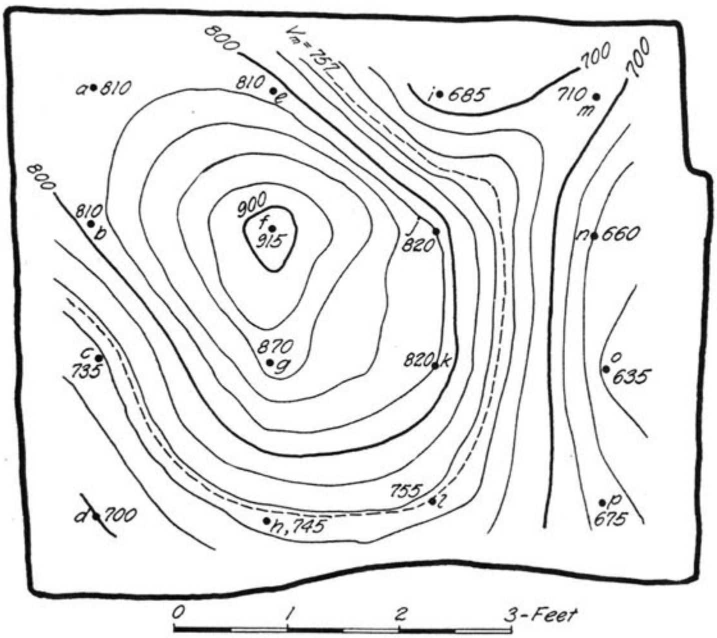

FIG. 8. ISOVEL DIAGRAM, NORMAL QUANTITY, SECTION C_2

not this is preferable to placing them between timbers cannot be said at present, as no tests were run with this point specifically in mind.

10. *Quantity Measurements.*—The outlines of section C_2 and the manner in which it was subdivided into 16 subsections are shown in Fig. 8, which also shows the isovel distribution for a traverse made with normal airflow when the mine was idle. Twelve traverses were made at this section at quantities ranging from less than 14 000 to more than 38 000 cubic feet per minute. Since the fan could be driven at only one speed it was necessary to change the airflow by the use of auxiliary regulators, opening of doors, etc. The quantity through section C_2 was reduced by using a canvas regulator between it and the airshaft at about $0 + 40$ and increased by closing the regulator east of the shaft and/or opening a small man door leading to the main return at the undercast. This was done, of course, only when the mine was idle. Six pairs of successive duplicate traverses were run, covering virtually a three-fold range in quantity. No two duplicate traverses differed from each other in quantity by as much as 4 per cent of their mean.

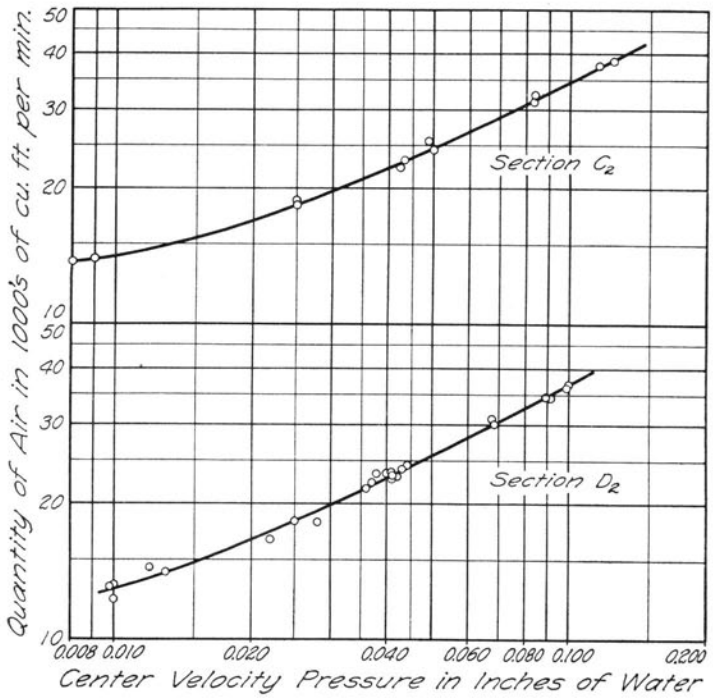

FIG. 9. RELATION OF QUANTITY TO CENTER VELOCITY PRESSURE, SECTIONS C_2 AND D_2

The relation of quantity to center velocity pressure at section C_2 is shown in Fig. 9 where the quantity is plotted logarithmically against net center velocity pressure. Like the corresponding curve for section A_2 at the Matthiessen and Hegeler mine (Fig. 3) this curve is slightly concave upward.

11. *Isovels.*—At the higher quantities all of the isovel diagrams (see Fig. 8) are of the same type, giving the effect of an eccentric elliptical bull's-eye with major axis inclined down to the right and the high velocity node to the left of the center (looking upstream). In each one there is an anomalous "island" of high velocity in the upper right corner (subsection m) sometimes separated from equally high velocities near the center of the section by a band of lower velocities. Since the quantities represented by isovel diagrams like Fig. 8 range from 18 500 to 38 200 cubic feet per minute, the uniformity in their appearance indicates a constancy in airflow distribution throughout this two-fold range in quantity. However, for two

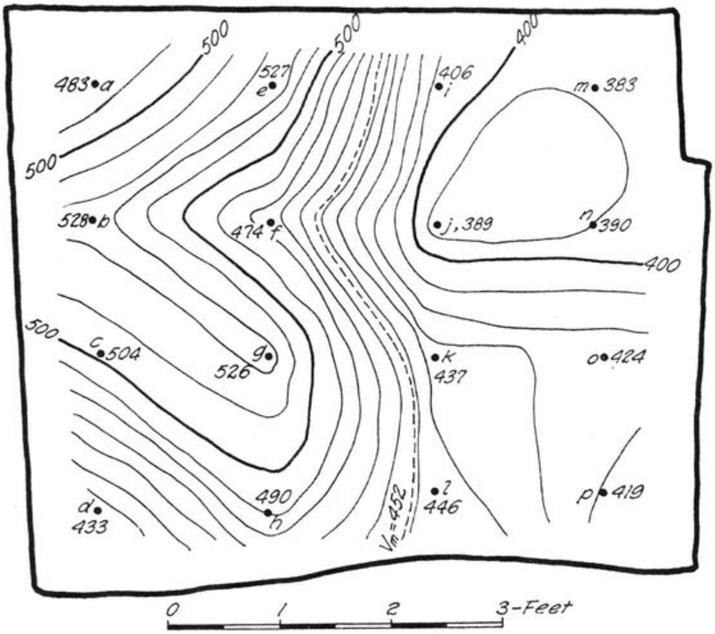

FIG. 10. ISOVEL DIAGRAM, LOW QUANTITY, SECTION C_2

Wahlen gage traverses run at a little less than 14 000 cubic feet per minute, there was apparently an entirely different velocity distribution (Fig. 10), essentially vertical in its alignment, and seemingly unrelated to the other distribution, save that the maximum velocities are found to the left of the center. This marked change may or may not have been gradual between about 14 000 cubic feet per minute, the quantity represented by Fig. 10, and 18 500 cubic feet per minute, the minimum quantity represented by Fig. 8, but if some such change took place at all of the cross-sections along the aircourse simultaneously one might expect a radical change in the pressure and energy losses as a result of such a marked internal readjustment in airflow.

12. *Pressure and Energy Losses.*—The principal resistance zone under investigation at this stage of the work was C_1–C_4 (Fig. 6), 258.5 feet in length. Five static pressure drop determinations were made for this unit at quantities ranging from 18 500 to 38 200 cubic feet per minute. On the overall basis k averaged $(246 \pm 2.6) \times 10^{-10}$ and on the clear basis $(92.6 \pm 0.94) \times 10^{-10}$.

TABLE 3

VALUES OF k FOR STRAIGHT ZONES, VERONA MINE BEFORE ALTERATION

Zones	Length ft.	Mean Cross-sectional Area sq. ft.		k* overall	k_c* clear	No. Determinations
		overall	clear			
C_1–C_2	56.1	54.6	37.8	.262	113	2
C_1–C_3	192.9	53.6	35.5	261 ± 4.5	98.8 ± 1.4	3
C_1–C_4	258.5	53.9	35.5	246 ± 2.3	92.6 ± 0.84	5
C_2–C_3	136.8	53.4	34.5	236 ± 2.3	82.9 ± 0.81	6
C_2–C_4	202.4	53.7	34.9	231 ± 5.0	82.4 ± 1.6	5
C_3–C_4	65.6	54.6	35.8	239 ± 1.9	88.3 ± 0.62	3

*In units of 1×10^{-10}

Next in importance among the resistance zones was C_2–C_3 (Fig. 6) which was 136.8 feet long, and without the expansion at the instrument station which C_1–C_4 contained. Six static pressure drop determinations were made for this zone at quantities between 13 800 and 38 200. The overall k is $(236 \pm 2.5) \times 10^{-10}$ and the clear k_c is $(82.9 \pm 0.89) \times 10^{-10}$. Both values are about 10 points lower than the corresponding values for C_1–C_3.

For C_2–C_4, 202.4 feet in length, the respective values of k on overall and clear bases are $(231 \pm 5.5) \times 10^{-10}$ and $(82.4 \pm 1.8) \times 10^{-10}$, respectively, showing higher probable errors than values previously given, due to wider variations from test to test. This may be due, in part, to the fact that in three out of the five determinations the quantity was based on center velocity pressure readings only.

These results and those of some additional determinations are given in Table 3. The table shows that, on the whole, zones including the instrument station expansion (C_1-zones) have higher values of k than the downstream units which do not contain such an irregularity. It seems probable that the higher resistance which causes the increase in k for the C_1-units is due primarily to this expansion, although this is by no means a certainty, as many less apparent differences between the various units may have been the cause. Comparison of the data of Table 3 with the corresponding data for the Matthiessen and Hegeler mine brings out strikingly the fact that while k on the clear basis is in essential agreement for the two mines, as is to be expected in view of the similarity of the two aircourses, on the overall basis k for the Verona mine is roughly 50 per cent greater than for the Matthiessen and Hegeler entries. This probably expresses the greater relative roughness of the Verona entry, the ratio of its overall to clear

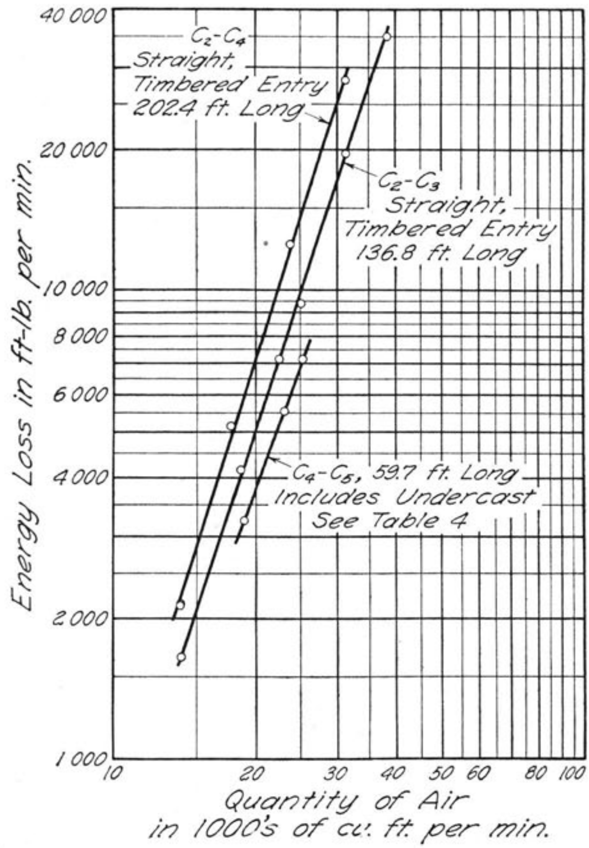

FIG. 11. ENERGY LOSS VS. QUANTITY, VERONA MINE BEFORE ALTERATION

mean area being about 1½ as compared with 1¼ for the Matthiessen and Hegeler entry.

The energy losses in the undercast zone C_4–C_5, and in a straight zone, C_2–C_4, are shown in Fig. 11. An analysis of the net undercast losses is made in Table 4, which shows the net energy loss incident to the presence of the undercast to be equal to that of roughly 40 to 50 feet of entry of the type represented by C_2–C_4.

IV. VERONA MINE AFTER ALTERATION

13. *Nature of Alterations.*—At this mine it was possible to improve portions of the aircourses on each side of the shaft, and later to

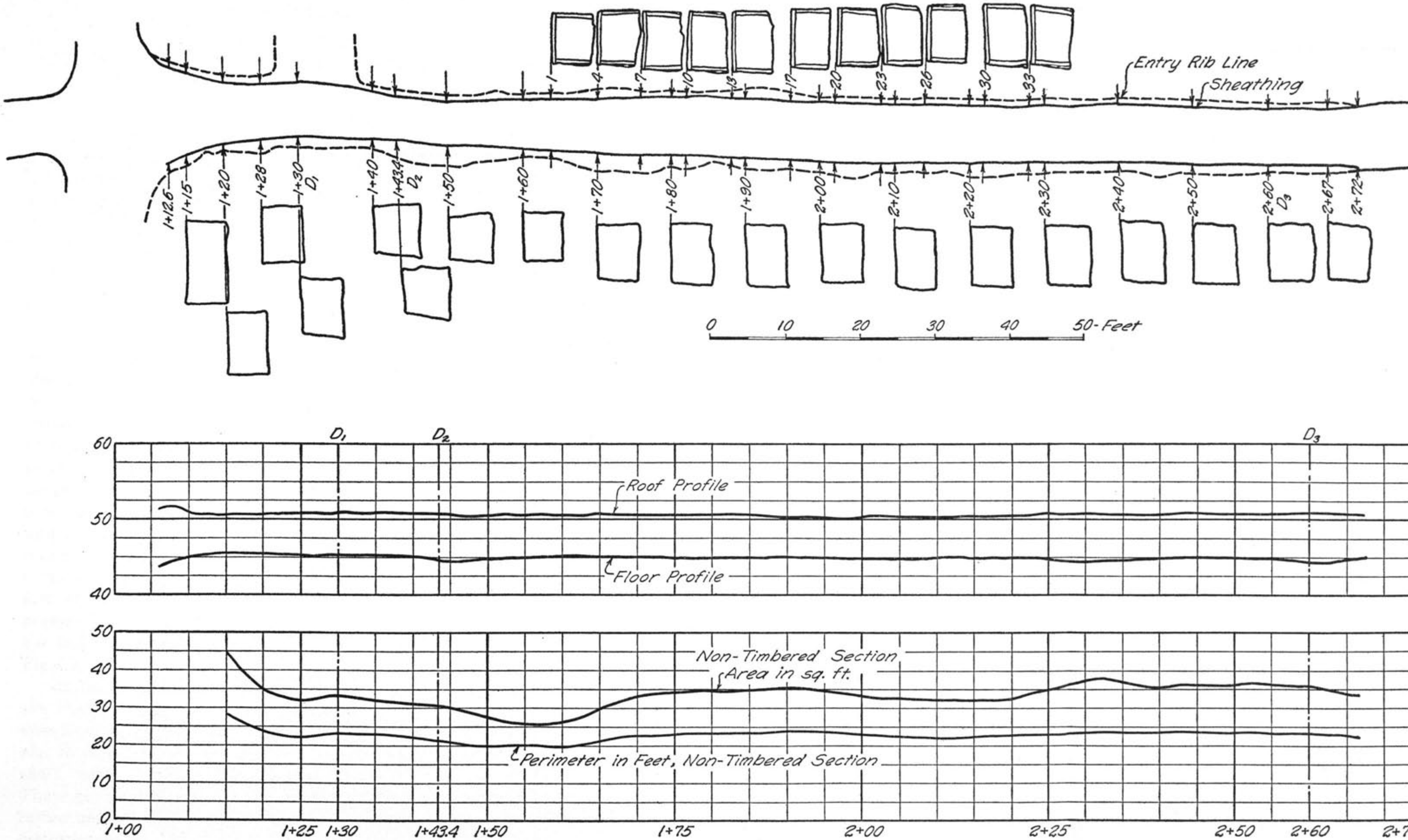

FIG. 12. PLAN AND PROFILE, MAIN AIRCOURSES, VERONA MINE AFTER ALTERATION

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TABLE 4

ENERGY LOSSES AT UNDERCAST, VERONA MINE

Energy losses are in ft. lb. per min.

	Quantity cu. ft. per min.	
	20 000	25 000
1. Energy loss, C_4–C_5, from Fig. 11	3 800	6 800
2. Energy loss in straight entry, C_2–C_4, from Fig. 11	7 100	14 200
3. Energy loss per foot of straight entry like C_2–C_4. Values of line 2 ÷ length of C_2–C_4 = (202.4 ft.)	35	70
4. Energy loss per 59.7 feet* of straight entry (= 59.7 × line 3)	2 100	4 200
5. Net energy loss due to undercast (line 1 − line 4)	1 700	2 600
6. Equivalent length of undercast (ft.) line 5 ÷ line 3	49	37

*Length of C_4–C_5.

introduce temporary timbering in varied arrangements in the west aircourse. Here the alteration consisted in a realignment of timber sets for about 170 feet below the instrument station. Following this the top and sides inside the timber sets were tightly sheathed over with 1 x 6-in. shiplap lumber, making a smooth surfaced airway over 150 feet in length. It is shown in plan and profile with appropriate area and perimeter curves in Fig. 12. It is evident from the cross-section diagrams and the areagraph that the cross-section was by no means uniform, ranging from 26 square feet at $1 + 60$ to 38 square feet, nearly a 50 per cent increase, at $2 + 30$, with numerous other minor fluctuations. However, variations in this item were obviously much less severe and abrupt than before the entry was sheathed. Cross-sections were measured every 10 feet along the sheathed zone and at such intermediate points as seemed desirable, permanent pressure cross-sections being located at $1 + 30$ (D_1 static section), $1 + 43.4$ (D_2 traverse section), and $2 + 60$ (D_3 static section) (see Fig. 12).

On the east side similar sheathing was installed just adjacent to the shaft, from $0 + 04.5$ to the timber set at $0 + 14.3$. As can be seen from the cross-section diagrams, this entry was extremely irregular in cross-sectional area and shape, being high and narrow at the shaft, nearly square at $0 + 11$, and low but wide beyond $0 + 15$. Three pressure sections were located in this aircourse, all of them rather unfavorably situated it is true, but unavoidably so due to the distortion of the entry. Traverse section E_1 is in the sheathed zone at $0 + 12$, traverse section E_2 is the door opening at $0 + 22.5$, and static section E_3 is at $0 + 48.6$ just outbye a split (see Fig. 6).

FIG. 13. LOOKING DOWNSTREAM THROUGH UNTIMBERED SHEATHING, VERONA MINE AFTER ALTERATION

14. *Quantity Measurements.*—The principal traverse section in the west aircourse was section D_2, where 25 traverses were made, the maximum air quantity being 37 000 and the minimum 12 300 cubic feet per minute. Detailed results are given in Table 5. The outlines of section D_2 and its manner of sub-division are shown in Figs. 14 to 16, inclusive. Sixteen traverse points were used in all except the last pair of traverses, in which 25 points were used. The logarithmic relation of quantity to center velocity pressure is shown in Fig. 9. It is represented by a curve of slight upward concavity like the corresponding curves for sections A_2 at the Matthiessen and Hegeler mine (Fig. 3) and C_2 at the Verona mine.

The results of tentative field quantity calculations were regarded with some doubt following the first few traverses at section D_2 with normal airflow, as they indicated a lesser quantity through the sheathed zone than had existed in the aircourse under normal conditions before the alteration. However, examination of the final data shows that the four normal traverses at section C_2 averaged

TABLE 5

QUANTITIES AT SECTION D_2, VERONA MINE AFTER ALTERATION

Area 30.9 sq. ft. Sixteen traverse points unless otherwise noted.

(1) Traverse	(2) Date (1928)	(3) Air	(4) Gage	(5) Net Cen. Vel. Pressure in. of water	(6) Quantity cu. ft. per min.	(7) Remarks	(8) Average	(9) Per cent Difference
1	July 21	n w	Ell.	0.040	23 300			
2	July 22	E bl. W sh.	"	0.100	37 000	duplicate traverses	36 650	1.9
3	July 22	E bl. W sh.	"	0.099	36 300			
4	July 22	W reg.	Wahl.	0.028	18 200	duplicate	17 550	7.4
5	July 22	W reg.	Ell.	0.022	16 900			
6	July 22	W reg.	Wahl.	0.010 0.0096*	13 100			
7	July 22	W sh.	Ell.	0.068	30 100	duplicate	30 350	1.7
8	July 22	W sh.	Ell.	0.067	30 600			
9	July 22	W reg.	Wahl.	0.010	12 300			
10	July 24	n w	Ell.	0.041	22 700	duplicate	22 550	1.3
11	July 24	n w	Ell.	0.037	22 400			
12	July 28	n i	Ell.	0.044	24 500	duplicate	24 250	2.0
13	July 28	n i	Ell.	0.043	24 000			
14	July 29	E bl. W sh.	Ell.	0.089	34 700	duplicate	34 750	0.29
15	July 29	E bl. W sh.	Ell.	0.092	34 800			

*Read on Wahlen Gage, otherwise Ellison gage.

n = normal airflow
w = mine working
i = mine idle
E = East aircourse
W = West aircourse

bl = blocked
sh = shorted
reg = regulated
Ell = Ellison Gage
Wahl = Wahlen Gage

TABLE 5.—Concluded

QUANTITIES AT SECTION D_2, VERONA MINE AFTER ALTERATION

Area 30.9 sq. ft. Sixteen traverse points unless otherwise noted.

(1) Traverse	(2) Date (1928)	(3) Air	(4) Gage	(5) Net Cen. Vel. Pressure in. of water	(6) Quantity cu. ft. per min.	(7) Remarks	(8) Average	(9) Per cent Difference
16	July 29	W reg.	Wahl.	.....	18 600	interlocking	18 350	2.7
16	July 29	W reg.	Ell.	0.025	18 100			
17	July 29	W reg.	Wahl.	.....	13 400	interlocking	13 750	5.1
17	July 29	W reg.	Ell.	0.013	14 100			
18	July 29	W reg.	Wahl.	.....	13 200	interlocking duplicate	13 800	8.7
18	July 29	W reg.	Ell.	0.012	14 400			
19	Aug. 2	n w	Ell.	0.036	21 900	simultaneous with $1D_3$		
20	Aug. 4	n i	Ell.	0.041	23 300			
21	Aug. 5	n i	Ell.	0.042	23 000	conditions of Traverse 20 but with 33 timber sets in sheathed zone.		
22	Aug. 5	n i	Ell.	0.041	22 900	dup. of Traverse 21	22 950	0.44
23	Aug. 7	n w	Ell.	0.038	23 300	simultaneous with $2D_3$		
24	Aug. 13	n i	Ell.	0.045	24 000	duplicate, 25 traverse points	23 850	1.3
25	Aug. 13	n i	Ell.	0.044	23 700			

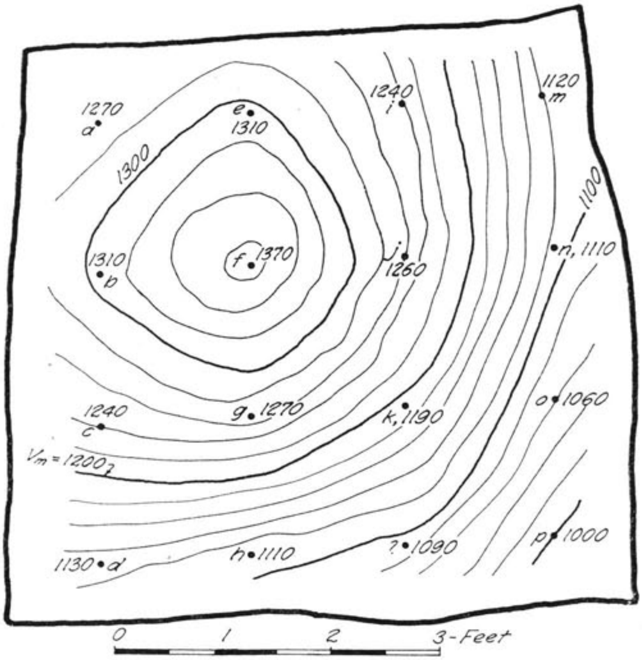

FIG. 14. ISOVEL DIAGRAM, HIGH QUANTITY, TRAVERSE 2 D_2, VERONA MINE AFTER ALTERATION

23 800 $\pm$ 560 cubic feet per minute, while the ten normal traverses run at section D_2 with the entry unobstructed averaged 23 300 $\pm$ 190 cubic feet per minute, a little lower amount it is true, but the difference (500 cubic feet per minute) is obviously not a significant one, as it is less than the probable error in the average quantity at section C_2. Hence, so far as can be judged from the data at hand the alteration did not appreciably affect the quantity of flow. Neither did the placing of 33 three-piece timber sets in the sheathed zone below section D_2 affect the quantity, as judged from the results of the two duplicate traverses (21 and 22 D_2) run with the timbers in place, which gave quantities of 23 000 and 22 900 cubic feet per minute, respectively (see Table 5).

Eight pairs of duplicate traverses were run at section D_2, this term being applied to two immediately consecutive traverses run with the same air coursing but with different observers and gages. The average quantities and per cent differences are shown in Table 5. Only one pair of duplicate traverses (4 and 5) show a high relative difference (7.4 per cent of the mean). While traverse 4 was made

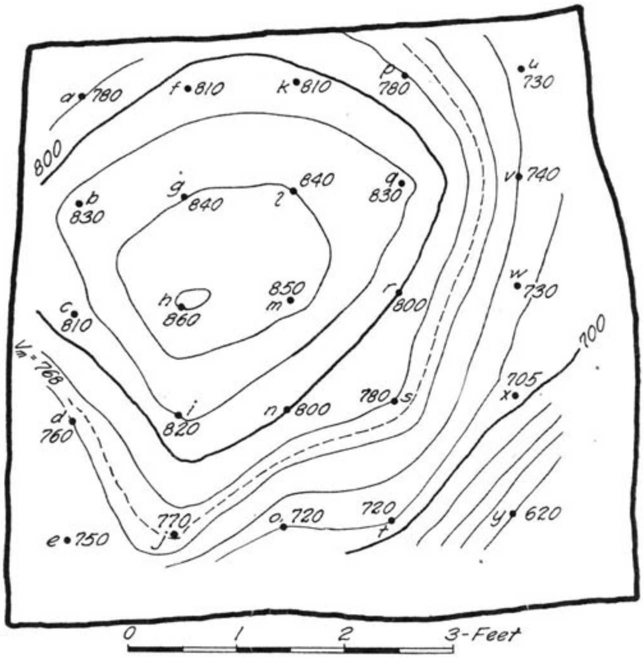

FIG. 15. ISOVEL DIAGRAM, NORMAL QUANTITY, TRAVERSE 25 D_2, VERONA MINE AFTER ALTERATION

with the Wahlen gage and traverse 5 with the Ellison gage, which might account for the discrepancy, there is a decided difference in net center velocity pressures (0.028 against 0.022 in. of water) in the two traverses, indicating an actual change in airflow due to some extraneous cause beyond experimental control.

Three pairs of interlocking Ellison-Wahlen traverses were run, all having relative differences greater than two per cent of the mean quantity. The scheme followed in traversing was to set the pitot tube at a given traverse point and read the velocity pressure on, say, the Ellison gage, then transfer the connections to the Wahlen gage, leaving the pitot tube undisturbed. After the velocity pressure had been read on the Wahlen gage the pitot tube was moved to the next traverse point, leaving the connections unchanged, and the new velocity pressure then read on the Wahlen gage. Finally the connections were changed to the Ellison gage and the process repeated. Thus two complete sets of velocity pressure readings were obtained for each traverse, and the quantities computed independently, with the results shown in Table 5.

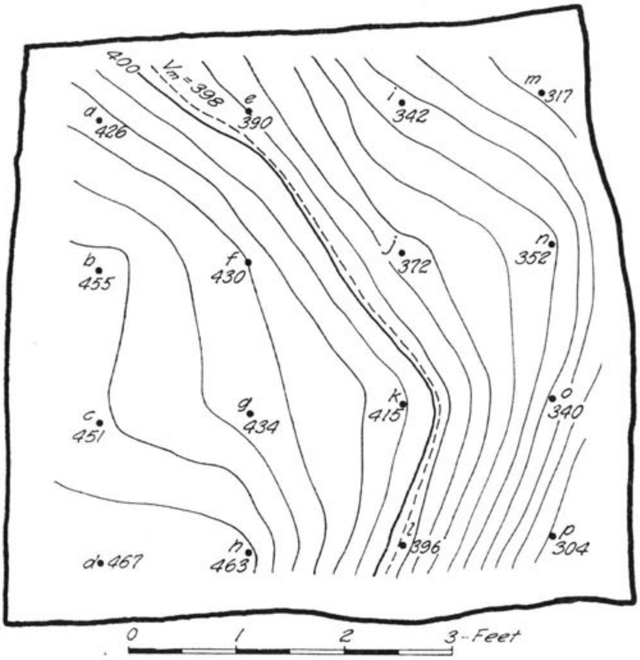

FIG. 16. ISOVEL DIAGRAM, LOW QUANTITY, TRAVERSE 9 D_2, VERONA MINE AFTER ALTERATION

The first of these traverses gave a Wahlen quantity of 18 600 and an Ellison quantity of 18 100 cubic feet per minute, the two values differing from each other by 1.4 per cent of the mean quantity (18 350 cubic feet per minute). An examination of the Ellison and Wahlen velocities for each subsection shows that the Ellison velocities are, on the whole, clearly lower than the corresponding Wahlen velocities, the difference averaging 14 feet per minute.

Traverses 17 and 18 D_2 were duplicate interlocking traverses in which the two Ellison quantities (14 100 and 14 400 cubic feet per minute) averaged 14 250 cubic feet per minute, considerably higher than the two Wahlen quantities (13 400 and 13 200 cubic feet per minute), which averaged 13 300 cubic feet per minute. Again, examination of the subsectional velocities shows that there was a consistent and substantial difference between the two gage results for a given velocity, the Ellison gage this time giving higher velocities in 30 out of the 32 cases, rather than lower velocities as before. This is obviously a condition which can hardly be attributed to changes in airflow in view of the alternation in the use of the two gages. Since

TABLE 6
SIMULTANEOUS TRAVERSES, VERONA MINE AFTER ALTERATION
Normal airflow, mine working

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Date (1928)	Upstream Section	Downstream Section	Upstream Q cu. ft. per min.	Down-stream Q cu. ft. per min.	Diff. (4)−(5) cu. ft. per min.	Net Cen. Vel. Press. Section D_2 in. of water
Aug. 2	$D_2(1+43.4)$	$D_3(2+60)$	21 900	20 600	1 300	0.036
Aug. 7	$D_2(1+43.4)$	$D_3(2+60)$	23 300	21 900	1 400	0.038
Aug. 11	1+20	2+40	23 300	22 500	800	0.042
Aug. 11	1+60	2+20	22 200	23 300	−1 100	0.040
Aug. 11	1+80	2+00	23 600	23 300	300	0.041

the same pitot tube and heavy connecting tube were used for both gages, it appears that the difference arose at the gages, due to a temporary lack of correspondence in the gage readings at like pressures.

Five pairs of simultaneous traverses were made at different sections in the sheathed zone, as shown in Table 6. Each pair of these traverses was run by setting a pitot tube at corresponding traverse points in each of two traverse sections, and reading the two velocity pressures in immediate succession before moving the pitot tubes to the next traverse point. In four of the five pairs of traverses there is a larger upstream quantity than downstream which is not an unreasonable result in view of possible leakage out of the entry, but the traverse at $1 + 60$ gave an appreciably lower quantity (22 200 cubic feet per minute) than that taken simultaneously at $2 + 20$, 60 feet farther downstream (quantity = 23 300 cubic feet per minute). This result would at first thought seem to point only to error in the results, as leakage of air back into the entry between the two sections would apparently be out of the question, until the plotted results shown in Fig. 12 are considered. Here it is seen that traverse station $1 + 60$ is at the most restricted portion of the entry, and it may be possible that a substantial portion of the air current (5 per cent or more would be required to correct the negative error of 1100 cubic feet per minute) leaked through the sheathing into the area between it and the entry roof and ribs upstream from $1 + 60$ and back into the entry proper again in the expanding zone of sheathing between $1 + 60$ and $2 + 20$. Further testing would be necessary to determine this point, but it should be borne in mind that the leakage quantity in question is relatively small (5 to 10 per cent of the total quantity) while the peripheral area without the sheathing is relatively large (30 to 40 per

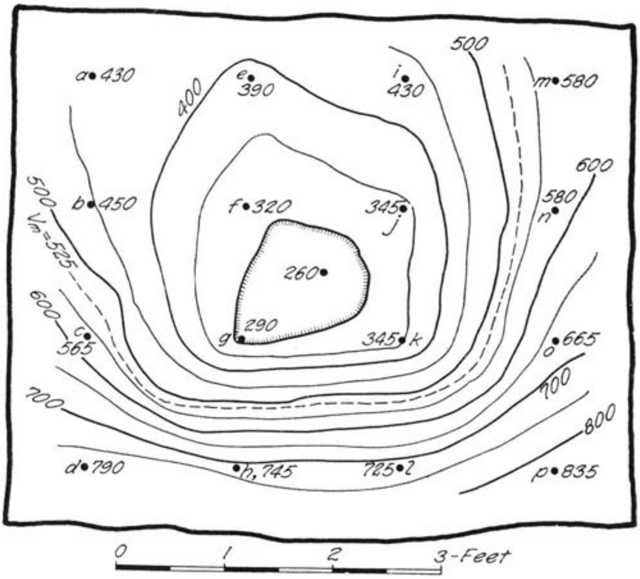

FIG. 17. ISOVEL DIAGRAM, TRAVERSE 2 E_1, VERONA MINE AFTER ALTERATION

cent of the overall cross-sectional area) so that a comparatively slow movement of air in the outer area would account for a relatively small quantity. Such a transference of air from inside the sheathing to outside of it and back again was very noticeable just above and below a temporary regulator installed later at section 2 + 01.

Inasmuch as the downstream quantities were, with the one exception noted, lower than the quantities simultaneously determined upstream, the assumption that there is no leakage out of the aircourse must be regarded with a good deal of suspicion; and the energy loss data are vitiated to the extent that this 5 to 6 per cent, or less, shortage in downstream quantities may very likely represent actual leakage rather than errors in quantity measurement. However, in view of the uncertainty of any corrections that might reasonably be applied to the energy loss data to compensate for this apparent leakage, it was thought better to disregard leakage and use the data as they stand.

Two traverse sections were used east of the shaft, the upstream one (E_1 at 0 + 12) being located in the sheathed zone one foot downstream from the throat of the constriction just inbye the shaft (Fig. 6), the downstream one (E_2 at 0 + 22.5) being the rectangular

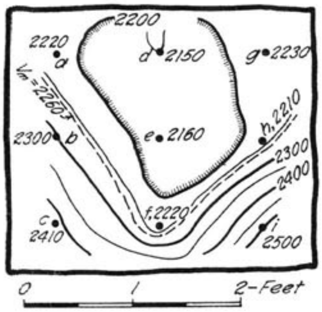

FIG. 18. ISOVEL DIAGRAM, TRAVERSE 1 E_2, VERONA MINE AFTER ALTERATION

manway aperture in an old regulator frame. The outlines and traverse points for these sections are shown in the isovel diagrams (Figs. 17 and 18, respectively). Two traverses were run at each section, the gages not being moved for this work, and simultaneous center velocity pressure readings were taken at section D_2 to permit an estimate of the total mine air quantity. The results are listed in Table 7, and are surprisingly consistent as to the two pairs of quantities at each section, considering the unusual and unfavorable setting of both traverse sections. The two traverses at section E_1 gave an average quantity of 13 900 cubic feet per minute, with a difference of 1000 cubic feet per minute, or 7.2 per cent of the mean quantity, while the two at section E_2 averaged 14 900 cubic feet per minute (about 7 per cent higher than at E_1) with a difference of 600 cubic feet per minute, or 4.0 per cent of the mean. The total indicated mine air quantity is about 37 000 cubic feet per minute under normal working conditions.

This completes the discussion of the season's quantity determinations, and on the whole it may be said that the results tend to increase the conviction that this method of traversing gives quantities which are not only fairly consistent but reasonably accurate.

15. *Isovels.*—As at section C_2 (p. 19) the isovel diagrams for section D_2 are of two types, one for higher quantities, above about 17 000 cubic feet per minute, and another for quantities below about 14 000 cubic feet per minute. There is a further correspondence with section C_2 in that the isovel diagrams for the higher quantities are eccentric bull's-eyes, while those for the lower quantities have an irregular vertical stratification. These features are brought out in Figs. 14 to

TABLE 7

QUANTITIES AT E_1 AND E_2, VERONA MINE AFTER ALTERATION

Airflow normal, mine working, Ellison gage
August 10, 1928

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Traverse	Section	E_1 Net Cen. Vel. Press. in. of water	D_2 Net Cen. Vel. Press. in. of water	Quantity cu. ft. per min.	Quantity at D_2 from Cen. Vel. Press. (see Fig. 9) cu.ft. per min.	Total Mine Quantity cu. ft. per min.
1................	E_1	0.006	0.040	13 400	22 800	36 200
2................	E_1	0.004	0.040	14 400	22 800	37 200
1................	E_2	0.005	0.039	15 200	22 400	37 600
2................	E_2	0.005	0.041	14 600	23 000	37 600

16 inclusive. Figure 14 represents traverse 2, section D_2 at the maximum quantity of 37 000 cubic feet per minute. While the lines are a little more regular than those of some of the other D_2 isovel diagrams, it is typical of the velocity distribution at higher quantities in having a high-velocity node about subsection *f* with velocities decreasing fairly uniformly in all directions therefrom. That this velocity distribution is by no means a result of the more or less accidental location of the 16 traverse points represented in Fig. 14 is shown by Fig. 15, which is quite like Fig. 14 save for the magnitude of the velocities involved. It represents traverse 25 D_2 run with 25 traverse points under normal idle conditions (air quantity = 23 700 cubic feet per minute).

The distribution in the lower quantity range is represented by Fig. 16 which shows the isovels for traverse 9 D_2 (air quantity = 12 300 cubic feet per minute). As just stated, there is a roughly vertical stratification of the isovel lines not seen in the previous diagrams, which indicates an essential redistribution of the airflow throughout the section. A thorough exploration of the state of transition between these two typical velocity distributions, not only at section D_2, but immediately above and below it, with accompanying energy loss determinations, might result in some valuable information as to the exact nature of the airflow through the transitory stage.

The isovel diagrams for the series of traverses run under normal working conditions every 20 feet along the sheathed zone (p. 30) were all of the bull's-eye type much like Figs. 14 and 15 with somewhat increasing regularity and symmetry farther downstream. This change is probably due to the cumulative ordering effect the smooth sheathed zone had on the airflow, in contrast with the disorder induced by the extreme roughness and irregularity of the preceding unsheathed entry.

Sections E_1 and E_2, east of the shaft, gave very unusual isovel diagrams in that each had its lower velocities near the center surrounded by higher velocities toward the periphery. This effect is shown in Figs. 17 and 18, representing traverses $2E_1$ and $1E_2$, respectively. It will be recalled that section E_1 is near the downstream end of a rapidly-contracting funnel of sheathing, the roof coming down sharply from the edge of the shaft to within a few feet upstream from the section. The roof and floor profiles are given in Fig. 6, which together with the plan, cross-sections, and areagraphs gives a good idea of the extreme irregularity of the entry here. Apparently the sloping roof just inbye the shaft deflected the air to the floor and sides in such a way as to leave little opportunity for orderly flow through the center, as is normally the case.

Somewhat similar conditions were obviously operative at section E_2, but there is a possibility that the apparently low velocities at the interior of these two sections may be due to an artificial lowering of an actually high velocity pressure by the impingement of transverse velocity components into the static ports of the pitot tubes, due to the rush of air from the wide upstream portion of the entry toward the narrow central opening of the two sections. Had circumstances permitted it should have been possible to verify the truth or falsity of this assumption by means of a differential static pressure survey within each section.

16. *Pressure and Energy Losses Prior to Timbering.*—During most of the traversing at section D_2 static pressure differentials were read between different pairs of the static sections previously discussed and shown in Fig. 12, all with the entry clear, however. Following this work, timber sets or other obstructions were placed in the entry in systematic fashion and additional static pressure drops measured, as will be shown in detail in the following discussion.

The zone of chief interest in this work is D_1–D_3 (Fig. 12) as it is the longest of those lying entirely within the sheathed zone. Twelve energy loss determinations were made for this zone at air quantities ranging from 18 200 to 37 000 cubic feet per minute. Three quantity determinations were based on center velocity pressure readings at section D_2 only. The results are shown in Fig. 19, where the energy loss in foot pounds per minute is plotted logarithmically against air quantity in cubic feet per minute. This figure also shows the losses in C_1–C_4 before and after sheathing for purposes of comparison. The

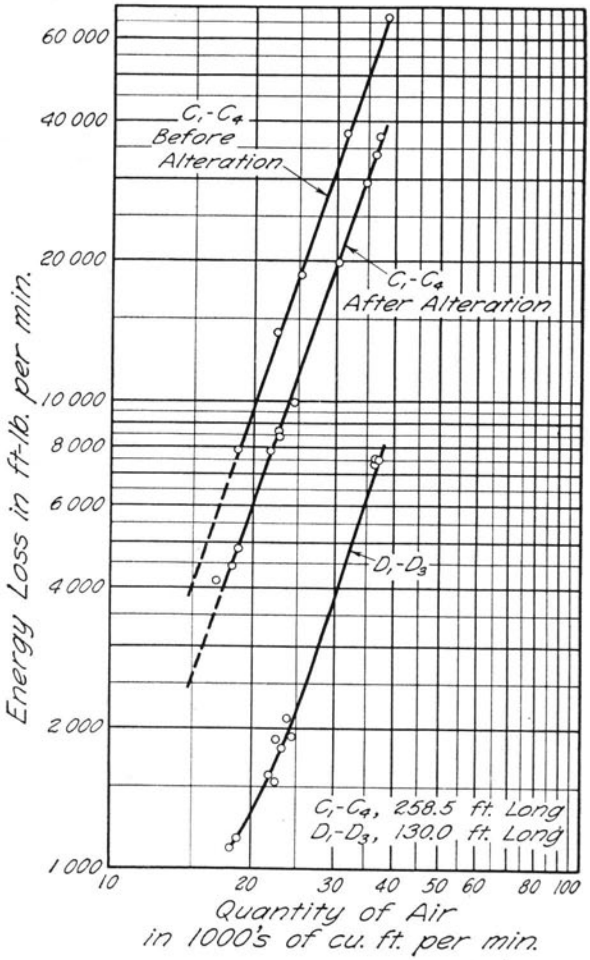

FIG. 19. ENERGY LOSS VS. QUANTITY, VERONA MINE BEFORE AND AFTER ALTERATION

D_1–D_3 points are surprisingly scattered in view of the better alignment obtained for points on the curve for the unsheathed units, where irregularities in results might be expected to be more, rather than less, pronounced. Values of k ranged from 17.0×10^{-10} to 24.0×10^{-10}, averaging $(20.1 \pm 0.45) \times 10^{-10}$. This average value of k, about 20×10^{-10}, is sharply in contrast with values of k obtained prior to sheathing of about 80 or 90×10^{-10} on the clear basis, or of about 240×10^{-10} on the overall basis.

TABLE 8

ENERGY LOSSES BEFORE AND AFTER SHEATHING, VERONA MINE

Energy losses are in ft. lb. per min.

	Quantity cu. ft. per min.		
	15 000	25 000	35 000
1. Energy loss per foot before sheathing (C_2–C_3) from Fig. 11, dividing by length = 136.8 ft.	15.2	72	195
2. Energy loss per foot after sheathing (D_1–D_3) from Fig. 19, dividing by length = 130.0 ft.	7.0	17	48
3. Reduction in energy loss per foot (1)–(2)	8.2	55	147
4. Per cent reduction in energy loss per foot $\frac{100 \times (3)}{(1)}$	54	76	75
5. Energy loss C_1–C_4 before sheathing, from Fig. 19	4 200	18 700	49 000
6. Energy loss C_1–C_4 after sheathing, from Fig. 19	2 600	11 500	31 000
7. Reduction in C_1–C_4 energy losses due to 160 feet of sheathing	1 600	7 200	18 000
8. Reduction in C_1–C_4 energy losses per foot of sheathing $\frac{(7)}{160}$	10	45	113

A direct comparison of the energy losses before and after alteration is given in Table 8, which shows a reduction of from about one-half to three-quarters in the energy loss per unit length of entry as a result of the alteration, dependent on the air quantity, a higher relative saving apparently accompanying the higher quantities. The table is self-explanatory, save that line 8 was intended as a rough check on line 3, which it apparently fails to be. However, at 15 000 cubic feet per minute the values for lines 2 and 6 were obtained by extrapolation (see Fig. 19), and hence are subject to relatively high errors. At the two higher quantities this relationship is reversed, as might be expected, inasmuch as energy losses incident to the entrance of the air into and departure out of the sheathed zone tend to reduce the net saving in C_1–C_4, while they, presumably at least, do not appear in D_1–D_3.

17. *Economics of the Improvement.*—A rough estimate of the economic features of the alteration may be of interest here. While exact figures are not available, the cost of this improvement was probably about $2.50 per foot, and from line 3, Table 8, we find the saving at a quantity of 25 000 cubic feet per minute, which is nearly the normal quantity, to be 55 foot pounds per minute, or 1.24 watts per foot of entry, which, for 8760 hours per year, gives a saving of 10.9 kilowatt hours per foot of entry per year. At a power cost of three cents per kilowatt hour, and assuming the overall efficiency of the fan and driving mechanism as 75 per cent, the saving in power bills is $\frac{10.9 \times 3}{0.75}$,

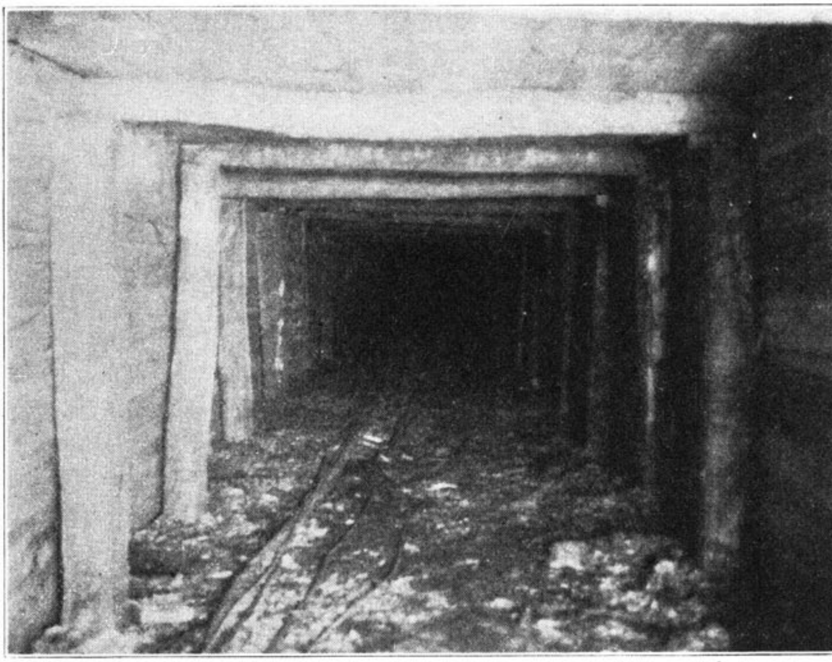

FIG. 20. TIMBER SETS IN PLACE IN SHEATHED ZONE, VERONA MINE BEFORE AND AFTER ALTERATION

or about 43 cents per foot per year. This represents a 17 per cent return on the expenditure for the improvement, but makes no allowance for maintenance, which would undoubtedly exceed the saving in power costs, although it might not be any higher after the alteration than before. If this latter assumption holds true, that is, that maintenance costs are not increased by the alteration, then there would apparently be ample justification for more widespread improvements of this sort where conditions are naturally very bad in the high velocity zone of the aircourses, as they are at this mine, and at many, if not most, others. Furthermore, if, due to the continual expansion of the mine, it becomes necessary to increase the air quantity, the energy savings would be much more marked, due to the rapid increase in power consumption with increasing quantity, while the improvement costs would remain unaffected.

18. *Pressure and Energy Losses with Timbers in Sheathed Zone.*— Following this work an extensive series of observations was made with various arrangements of timbers in the sheathed portion of the entry,

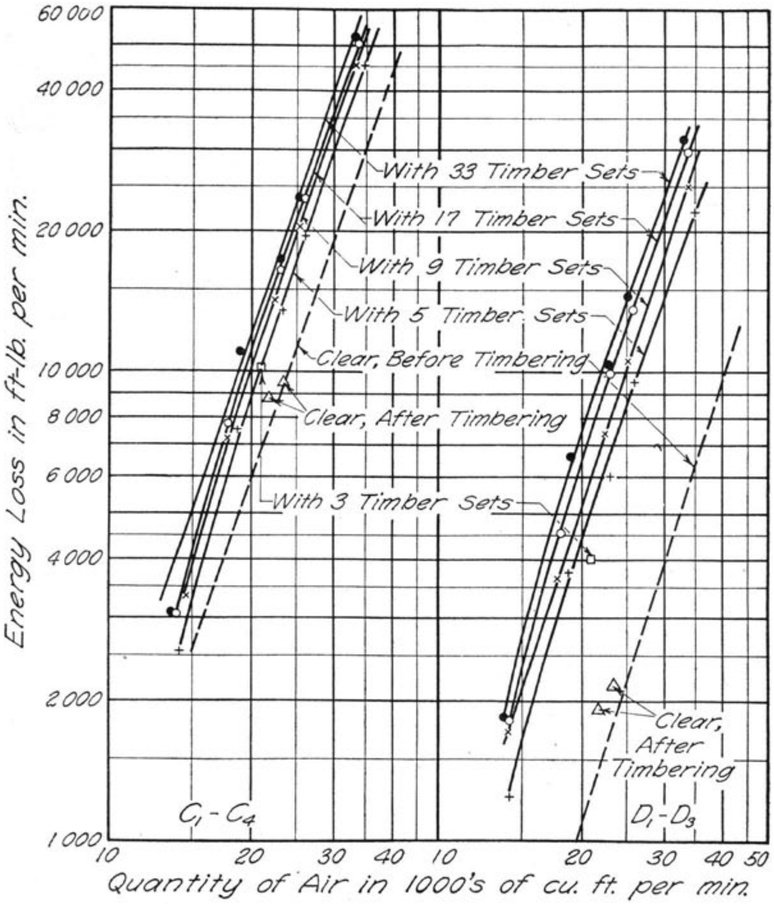

Fig. 21. Energy Loss vs. Quantity, Timber Sets in Sheathed Zone, Verona Mine

quantities being determined at section D_2 and static pressure drops from C_1 to C_4, and from D_1 to D_3. The first series involved the installation of 33 three-piece timber sets, each consisting of two side posts and a cross-bar, at two-foot intervals going downstream from section 1 + 64 to section 2 + 28. This left a clearance of a little over 20 feet between traverse section D_2 and the first timber set, which should assure freedom from the communication to section D_2 of any disturbances in airflow set up by the timbers. There was also a clearance of over 30 feet between the last downstream timber set (No. 33) and static section D_3. This is only about 5 or 6 diameters, it is true, but such a limited allowance represented a compromise between a more liberal one and the necessity of putting in an adequate number of timber sets to give reliable results. The cross-bars were mainly round timbers 8 to 10 inches in diameter, while some of the posts were split from such timbers, giving them a semi-circular or roughly triangular cross-section. Others were smaller round timbers which had been cut with two parallel surfaces to serve as ties in the mine track. Five of these measured at random averaged 4½ x 6 in. in cross-section. This type was used as center posts in a later group of observations. The sets were numbered consecutively from the upstream to the downstream end of the series, the exact locations and the cross-section diagrams for a number of them being shown in Fig. 12, which also shows the roof and floor profiles, and the graphs of area and perimeter of the mapped cross-sections.

Five simultaneous energy loss determinations were made for units C_1–C_4 and D_1–D_3 with the 33 timber sets in place, at quantities ranging from 13 700 to 33 200 cubic feet per minute. Only one quantity was determined by traverse, the remainder being based on center velocity pressure readings at section D_2. The results are shown in Fig. 21, where the energy loss in foot pounds per minute per resistance zone is plotted against quantity for each grouping of timber sets. Additional energy loss determinations were made for units C_1–D_3 and D_1–C_4 at normal quantity, and a comparison of the combination of these to give a derived energy loss for C_1–C_4 with the observed energy loss from C_1 to C_4 shows an agreement of within 3 per cent between the two values.

An analysis of the energy losses due to the presence of the timber sets is given in Table 9, where the net energy loss due to the timbers is calculated both from the C_1–C_4 losses (line 6) and the D_1–D_3 losses (line 9). While the results by these two methods disagree with each other by from 5 to 8 per cent, it must be remembered that they are based not only on center velocity pressure readings for quantity, but also on graphical interpolation from the logarithmic energy loss against quantity charts as well, so the discrepancies apparent between lines 6 and 9 of the table do not seem to be out of reason. Line 16 shows the pro rata losses for each of the 33 timber sets to be equal to those due to about 20 feet of the clear sheathed aircourse, as represented by D_1–D_3.

For the next series of tests the even-numbered timber sets were removed, leaving in place 17 sets at 4-ft. intervals, extending over the same portion of the aircourse (from section $1 + 64$ to section $2 + 28$). These energy losses also are plotted against quantity in Fig. 21. The

TABLE 9

ENERGY LOSSES DUE TO TIMBER SETS IN SHEATHED ZONE, VERONA MINE AFTER ALTERATION

Energy losses are in ft. lb. per min.

1. No. of Sets	33		17		9		5	
2. Center to center distance between sets (ft.)	2		4		8		16	
3. Quantity (cu. ft. per min.)	20 000	30 000	20 000	30 000	20 000	30 000	20 000	30 000
4. Energy loss C_1–C_4 with timber sets from Fig. 21	12 000	40 000	11 200	36 500	10 200	33 500	9 000	29 300
5. Energy loss C_1–C_4 without timber sets, from Fig. 21	6 000	19 000	6 000	19 000	6 000	19 000	6 000	19 000
6. Net energy loss due to timber sets, line (4)–(5)	6 000	21 000	5 200	17 500	4 200	14 500	3 000	10 300
7. Energy loss D_1–D_3 with timber sets	7 600	23 500	6 500	21 000	5 300	17 000	4 500	13 800
8. Energy loss D_1–D_3 without timber sets	1 100	3 900	1 100	3 900	1 100	3 900	1 100	3 900
9. Net energy loss due to timber sets, line (7)–(8)	6 500	19 600	5 400	17 100	4 200	13 100	3 400	9 900
10. Average net energy loss due to timber sets $\frac{(6)+(9)}{2}$	6 300	20 300	5 300	17 300	4 200	13 800	3 200	10 100
11. Average net energy loss per foot due to timber sets $\frac{(10)}{130.0}$	48.5	156	40.8	133	32.3	106	24.6	77.6
12. Per cent reduction in net energy loss due to timber sets from that due to 33 sets	......	......	15.9	14.8	33.3	32.0	49.2	50.3
13. Net energy loss per timber set due to timbers $\frac{(10)}{\text{no. of sets}}$	191	615	312	1 020	467	1 530	640	2 020
14. Per cent increase in net energy loss per timber set over that due to 33 sets	......	......	63.4	66.0	144	148	235	228
15. Energy loss D_1–D_3 clear per foot $\frac{(8)}{130.0}$	8.5	30	8.5	30	8.5	30	8.5	30
16. Equivalent length per timber set (ft.) $\frac{(13)}{(15)}$	23	21	37	34	55	51	75	67
17. Net energy loss per ft. due to each timber set $\frac{(13)}{(2)}$	96	308	78	255	58	191	40	126
18. Relative loss per ft., timbered to clear $\frac{(15)+(11)}{(15)}$	6.7	6.2	5.8	5.4	4.8	4.5	3.9	3.6

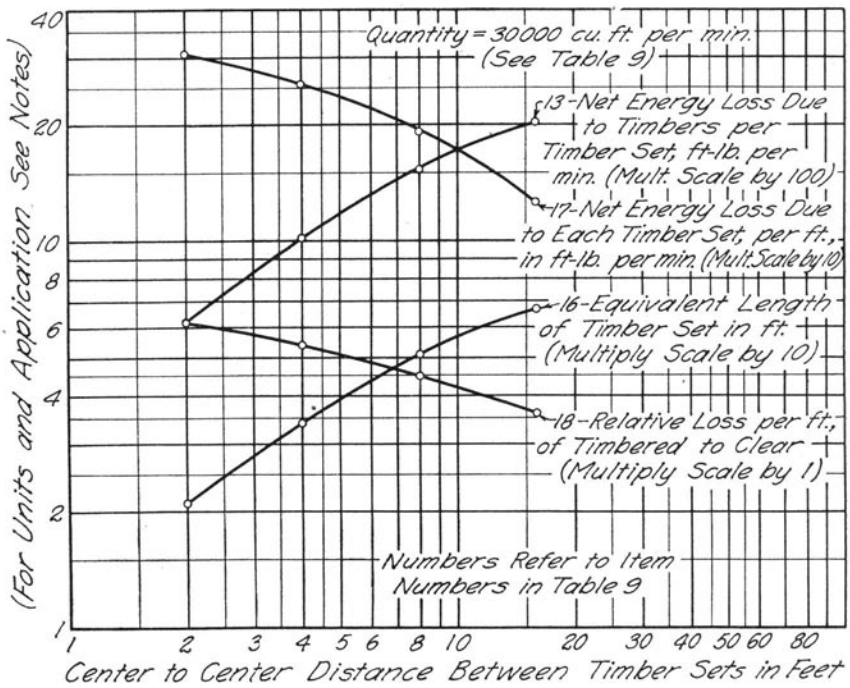

FIG. 22. EFFECT OF VARIED SPACING OF TIMBER SETS

data taken from these curves at 20 000 and 30 000 cubic feet per minute are presented in Table 9, as were those for 33 sets. Line 12 of Table 9 shows that the removal of the 8 timber sets has reduced the net energy loss due to timber sets about 15 per cent, whereas the loss caused by a timber set has increased from that for about 20 feet of clear sheathed entry to that due to 35 feet of similar entry (line 17). The relative loss in the timbered section to that in the clear sheathed section has decreased from about 6.5 to 5.5 (line 18).

The next alteration was the removal of 8 more timber sets, leaving in place nine sets (numbers 1, 5, 9, etc.) on 8-ft. centers. Table 9 shows that virtually a 50 per cent reduction in the number of timber sets (17 to 9) gives only roughly about a 30 per cent reduction (line 12) in net energy loss due to all timber sets, and that the net energy loss per timber set is 1.5 times as great as with 33 sets (line 14). Hence the equivalent length of clear sheathed entry for each timber set in feet (line 16) is increased, but, due to the longer distance between sets (8.0 feet on centers) the net energy loss per linear foot of entry per timber set is decreased (line 17). Finally, the ratio of the energy loss

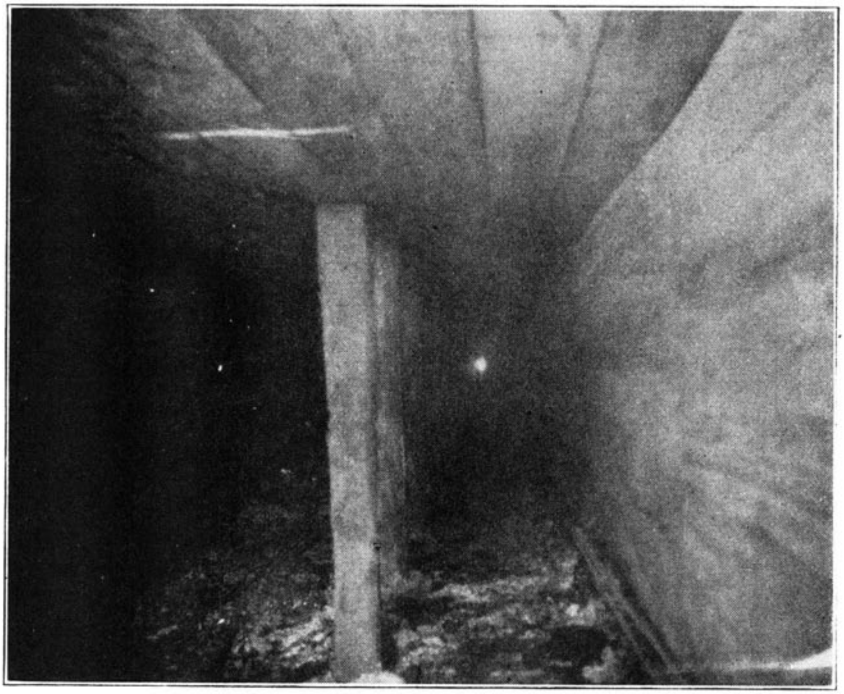

FIG. 23. CENTER POSTS IN PLACE IN SHEATHED ZONE

in the sheathed zone with timber sets to that without is reduced from about 5.5 or 6 to 1 to more nearly 4.5 to 1, incident upon this reduction in the number of timber sets.

The energy losses with 9 and 5 timber sets are also shown in Fig. 21. In addition it includes a point on each curve (C_1–C_4 and D_1–D_3) for 3 timber sets and two points for the clear entry after the removal of the timbers. These points (for clear entry) lie a little above the corresponding curves for energy loss before the timbers were installed. This increase in clear-entry losses is probably due to increased roughness of the floor caused by some digging which was done to install many of the side props. This left the floor appreciably rougher after the timbers were removed than it had been before they were put in.

The data of lines 13, 16, 17, and 18 of Table 9 for a quantity of 30 000 cubic feet per minute are plotted versus spacing of sets in Fig. 22. Logarithmic ruling was used simply to compact the plotting which covers a wide range of ordinates, rather than to bring out any possible exponential relationships. The net energy loss per timber set and equivalent length of clear sheathed entry per timber set (curves 13

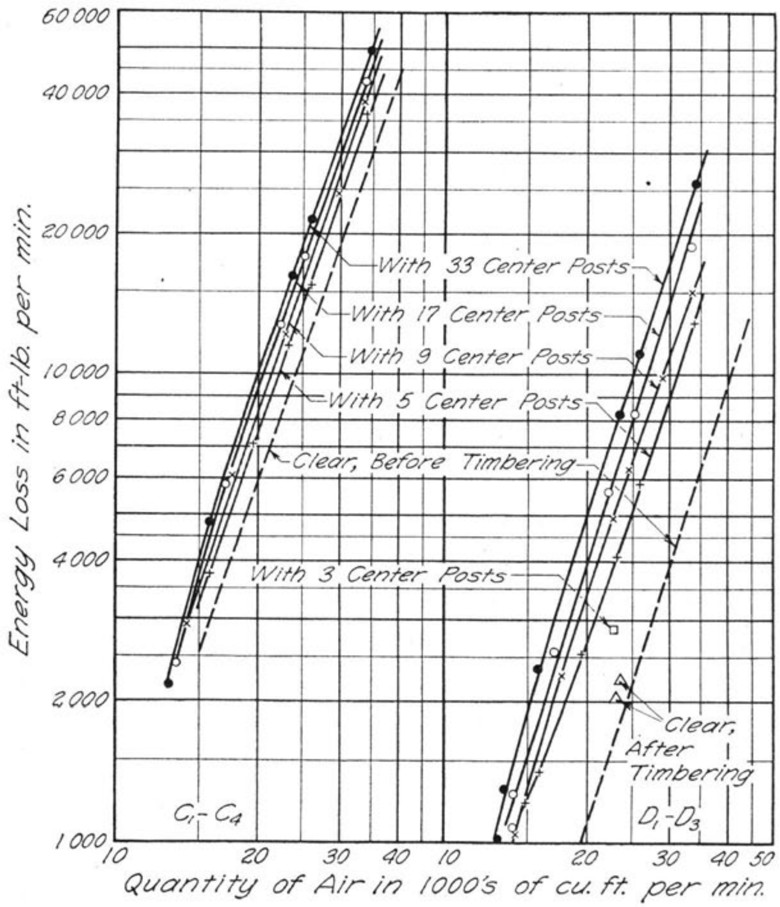

FIG. 24. ENERGY LOSS VS. QUANTITY, CENTER POSTS IN SHEATHED ZONE, VERONA MINE

and 16) both rise with increasing distance between sets. The net energy loss due to each timber set per foot of entry and the ratio of relative loss of timbered to clear entry per foot (curves 17 and 18) both decline with increasing spacing.

In correspondence with the timber set tests a later series of tests was run with center posts only put in the sections previously occupied by the three-piece timber sets. The energy losses in C_1–C_4 and D_1–D_3 are plotted logarithmically against quantity in Fig. 24 for 33, 17, 9, and 5 center posts in place respectively.

TABLE 10

ENERGY LOSSES DUE TO CENTER POSTS IN SHEATHED ZONE, VERONA MINE AFTER ALTERATION

Energy losses are in ft. lb. per min.

1. No. of Posts	33		17		9		5	
2. Center to center distance between posts (ft.)	2		4		8		16	
3. Quantity (cu. ft. per min.)	20 000	30 000	20 000	30 000	20 000	30 000	20 000	30 000
4. Energy loss C_1–C_4 with posts, from Fig. 24	10 000	32 500	9 100	30 000	8 350	27 300	7 500	24 500
5. Energy loss C_1–C_4 without posts, from Fig. 24	6 000	19 000	6 000	19 000	6 000	19 000	6 000	19 000
6. Net energy loss due to posts, line (4) − (5)	4 000	13 500	3 100	11 000	2 350	8 300	1 500	5 500
7. Energy loss D_1–D_3 with posts, from Fig. 24	5 050	16 800	3 980	14 200	3 400	10 500	2 620	8 800
8. Energy loss D_1–D_3 without posts, from Fig. 24	1 100	3 900	1 100	3 900	1 100	3 900	1 100	3 900
9. Net energy loss due to posts, line (7) − (8)	3 950	12 900	2 880	10 300	2 300	6 600	1 520	4 900
10. Average net energy loss due to posts $\frac{(6) + (9)}{2}$	3 980	13 200	2 990	10 650	2 330	7 450	1 510	5 200
11. Average net energy loss per ft. due to posts $\frac{(10)}{130.0}$	30.6	101.5	23.0	81.8	17.9	57.3	11.6	40.0
12. Per cent reduction in net energy loss due to posts from that due to 33 sets	......	......	24.9	19.3	41.5	43.6	62.0	60.6
13. Net energy loss per post due to posts $\frac{(10)}{\text{No. posts}}$	121	400	176	626	259	828	302	1 040
14. Per cent increase in net energy loss per post over that due to 33 posts	......	......	45.5	56.5	114	107	150	160
15. Energy loss D_1–D_3 clear per foot $\frac{(8)}{130.0}$	8.5	30	8.5	30	8.5	30	8.5	30
16. Equivalent length per post (ft.) $\frac{(13)}{(15)}$	14.2	13.3	20.7	20.9	30.4	27.6	35.5	34.7
17. Net energy loss per ft. due to each post $\frac{(13)}{(2)}$	61	200	44.0	157	32.4	104	18.9	65.0
18. Relative loss per ft., timbered to clear $\frac{(15) + (11)}{(15)}$	4.6	4.4	3.7	3.7	3.1	2.9	2.4	2.3

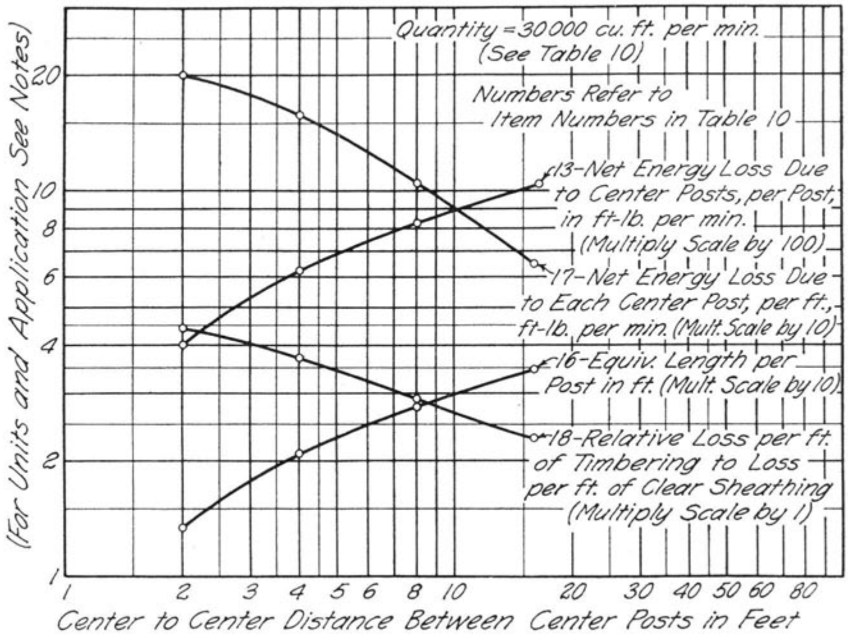

FIG. 25. EFFECT OF VARIED SPACING OF CENTER POSTS

Table 10 corresponds with Table 9 in that it analyzes the energy losses with center posts just as Table 9 does those with timber sets. A comparison of the net energy loss due to the posts as derived from the losses in C_1–C_4 and in D_1–D_3 (lines 6 and 9, Table 10) is not very assuring, as the former loss is in many cases considerably greater than the latter. This excess is more marked at the higher quantity (30 000 cubic feet per minute) not only for the center posts but for the timber sets as well (see Table 9), which indicates that it may be largely due to an increased flow of air in the peripheral area behind the sheathing at higher velocities. This would give rise to comparatively lower velocities and pressure losses within the sheathing with the result that the net energy loss due to timbers computed from the D_1–D_3 static pressure drop would be less than that computed from the C_1–C_4 static pressure drop, the airflow at these latter sections being unaffected by changes of flow within and without the sheathing.

Line 10 of Table 10 shows that the average net energy loss due to posts only decreases with decreasing number of posts for both air quantities (20 000 and 30 000 cubic feet per minute) as is, of course, to be expected. The relative loss with respect to the losses incident to the presence of 33 posts is given in line 12. It ranges from about 20 per cent with 4-ft. centers to 60 per cent with 16-ft. centers. However, the net energy loss per post due to posts rises with decreasing number of posts as is evident from line 13. This is plotted in Fig. 25 which corresponds to Fig. 22 for timber-set data. Line 14 of Table 10 shows the relative increase in the net loss due to each post with respect to that with 33 posts in place. It ranges from about a 50 per cent increase with 17 posts in place to 3 times as great an increase (150 to 160 per cent) with only 5 posts in place.

The equivalent length in feet of clear entry like D_1–D_3 for each post, as a producer of energy losses, is given in line 16 and plotted in Fig. 25. It more than doubles in magnitude from about 13 feet for posts on 2-ft. spacing to about 35 feet for posts at 16-ft. centers (5 posts).

The net energy loss occasioned by each post per foot of aircourse is given in line 17, and shown in Fig. 25, where it is represented by a curve sloping downward from a net energy loss of 200 foot pounds per minute per foot of entry for posts on 2-ft. centers, to one of 65 foot pounds per minute per foot of entry for posts on 16-ft. centers, at 30 000 cubic feet per minute. That is to say, that while the absolute net energy loss occasioned by each post (line 13) increases with increasing spacing of posts, the net energy loss per foot of entry decreases due to a relatively much more rapid increase in spacing than in absolute net energy loss per post. Finally, the ratio of loss per foot with posts to loss per foot of clear entry (line 18) drops from about 4.5 with 2-ft. spacing to less than 2.5 with 16-ft. spacing (see Fig. 25 also). It is this last item which shows clearly in both Tables 9 and 10 the increasingly bad effects of added obstructions in an aircourse. The fact that this ratio runs about 50 per cent higher for timber sets (Table 9) than for center posts (Table 10) with fair consistency from 2-ft. to 16-ft. spacing, indicates the relative merits, or better perhaps, demerits, of the two methods of timbering in so far as airflow is concerned.

V. Summary and Conclusions

19. *Summary and Conclusions.*—Quantities and static pressure drops were measured, by methods previously developed, in irregular entries timbered with three-piece sets in two different mines.

As in the past, duplicate velocity pressure traverses in some sections very unfavorably situated in irregular entries gave quantities checking within a few per cent of each other, no very serious discrepancies being encountered throughout the work which was done over a three to four-fold range in mean velocities.

As for the distribution of velocities within a section, there was a tendency for each section to have two typical distributions, as shown by isovel diagrams; one an eccentric bull's-eye at higher quantities, the other having a rough vertical isovel stratification at lower quantities.

The difficulty of satisfactorily expressing the results of pressure or energy loss measurements for entries of this type has been pointed out, and the plan of expressing k on the basis of both the average dimensions of the entry proper outside of the timbers (overall) and the average dimensions inside the timbers (clear) was arbitrarily chosen, it being recognized that both methods have some advantages. The principal results obtained were as follows:

(1) Based on the clear dimensions k_c was found to be about 90×10^{-10} for both mines, which is in fair agreement with a k_c of 80×10^{-10} reported by the United States Bureau of Mines for entry similarly timbered. On the overall basis k was less consistent from one resistance zone to another, ranging from about 150×10^{-10} to 250×10^{-10}. It averaged about 50 per cent higher at one mine than at another, presumably due to greater relative difference in overall and clear dimensions. The corresponding values of k_c averaged but about 10 per cent higher.

(2) The net pressure and energy losses due to a combined 70 deg. bend and dead end, and to an undercast, were computed. The pressure loss due to the former was about 1.7 times the velocity pressure and its energy loss equivalent to the energy loss in about 20 to 30 feet of straight timbered entry. The net energy loss due to the undercast was found to be equal to that of about 40 feet of such entry.

(3) It was found that sheathing the inside timber surfaces of about 160 feet of entry reduced the energy losses in that length from one-half to three-quarters, dependent on the air quantity, the higher relative savings accompanying the higher quantities.

(4) At the low quantities prevailing in this aircourse, it is estimated that the annual saving in power costs incident to the lowered resistance to airflow of the sheathed entry is about 15 to 20 per cent of the cost of the improvement. From this is to be deducted any increase in the cost of maintaining the aircourse due to the alteration. However, at the higher velocities which are frequently encountered in such aircourses, there would be a

marked increase in the saving, which would probably more than offset any increased cost of maintenance.

(5) Retimbering the sheathed zone with three-piece timber sets and with center posts at different spacings increased the energy losses over those of the untimbered sheathing markedly. It was found that, while at a given air quantity the net energy loss due to each timber set or post increased with increased spacing between timber sets or posts, the energy loss of an entry obstructed with timber sets or posts relative to that of an equal length of unobstructed sheathed entry decreased with increased spacing between obstructions. This is due to the fact that the net energy loss occasioned by each obstruction increased relatively less rapidly than did the spacing between obstructions. Neither the installation of the sheathing nor its subsequent retimbering had any noticeable effect on the quantity.

The work represented in this report supplements the results of previous investigations in supplying information as to the losses in closely timbered entries, the energy saved by smoothing up such an entry, and the losses caused by three-piece timber sets and center posts placed on various centers.

ILLINOIS COAL MINING INVESTIGATIONS

(Coöperative Agreement)

Engineering Experiment Station, University of Illinois

State Geological Survey Division

U. S. Bureau of Mines†

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*Bulletin 10. Coal Resources of District I (Longwall): by G. H. Cady. 1915.
Bulletin 11. Coal Resources of District VII: by Fred H. Kay. 1915. *Price, $1.00.*
Bulletin 14. Coal Resources of District VIII (Danville): by Fred H. Kay and K. D. White. 1915. *Price, 75 cents.*
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